3D Printed Probe for Simultaneous E and H Fields Measurements

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***Abstract*—Additive manufacturing using conductive polylactic acid (PLA) is an emerging technology. This work presents a double-loaded loop probe made of conductive PLA and evaluates its performance compared to a previous design built on a printed circuit board (PCB). The results show that constructing near-field probes using 3D printing with conductive PLA is feasible.**

***Keywords*—3D printing, near-field, double-loaded loop, polylactic acid, PLA, conductive PLA**

I. INTRODUCTION

The interest of measuring electromagnetic fields inside small closed volumes, such as shielding cases, small cubicles in vehicles or closed bays in airplanes, suggests the convenience of measuring simultaneously electric and magnetic fields. This requires near field probes suitable to be included in those compartments. As an example, the aeronautic industry is interested in probes to be fitted into composite fuselages instead of placing them in the middle of the bay [1]. Double-loaded loops have been proved to be suitable as near-field frequency-selective probes to measure the electric and the magnetic fields simultaneously. A double-loaded probe made on a flexible printed circuit board (PCB) that can be attached to the walls of those mentioned compartments is presented in [2]. Currently, 3D printing technology using novel materials such as conductive polylactic acid (PLA) brings the possibility of printing non-invasive near-field probes that can be fitted to a cavity or even constructing the probe within a 3D printed structure.

A double-loaded loop probe is a loop with two gaps at opposite sides loaded with identical loads. The theory of double-loaded loops was described in depth by King in 1969 [3]. Since then, several authors have presented different implementations of double-loaded loops intended for near-field measurements [4], [5]. The presence of an electromagnetic field induces a current within the loop, which is the contribution of the E-Field and the H-Field (Fig. 1). This means that the response of a double-loaded loop is, in essence, the superposition of an electric dipole and a magnetic loop. The information related to the E-field and the H-field can be obtained by the addition and the subtraction of the signals measured at each gap in the loop. Consequently, this kind of loops can be used to measure E and H fields simultaneously in the frequency or the time domains. Subsequently, other works contributed to the development of some theoretical or practical aspects. Some of those designs reduced the size of the loop and incorporated electro-optical links to transmit the signals, making it possible to use double-loaded loops as near-field probes [6], [7].

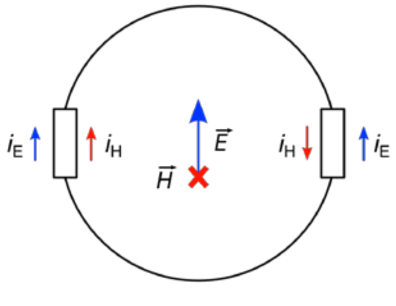

Fig. 1. Currents induced in the loop by the electric and magnitic fields.

The use of conductive PLA to construct a double-loaded loop raises important issues regarding its electromagnetic behaviour. The electrical characteristics of conductive PLA are not completely specified at radio frequencies. The "soldering" of the electronic components to the traces or "wires" made of conductive filament is yet another challenge.

The aim of this work is to evaluate the feasibility of using 3D printing with conductive PLA to build a near-field probe with similar performance to previous designs made of PCB. In this work, a probe made of conductive PLA and the experiment to obtain its response to the electromagnetic fields are presented. The results are compared to the response of a previous design of an equivalent double-loaded loop probe made on a PCB [1].

II. DESIGN AND CONSTRUCTION OF THE PROBE

A. Structure of the probe and electronic circuits

The probe we are considering as a reference is described in [1]. It is a double-loaded loop, 10 cm in diameter, implemented on a PCB. The loop is a copper trace 2 mm wide over a FR4 substrate. The loads are the intrinsic impedance of

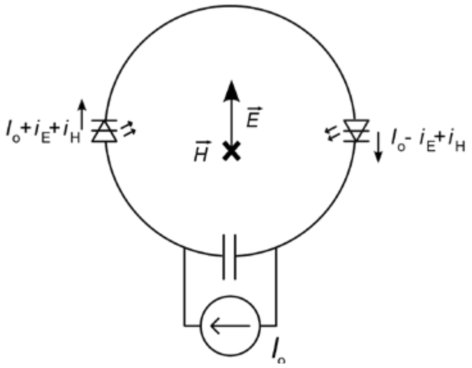

Fig. 2. Double-loaded loop probe with laser transmitters.

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the transmitting lasers. As it can be seen in Fig. 2, there is no electronic circuit beside the gaps to condition the signals. The only electronic circuit is a constant current source to bias both lasers. The currents due to the measured fields modulate the light of each laser which is sent over an optical link with a bandwidth of 2.5 GHz. The current source is powered with a 9 V battery.

At the reception side, the optical detector circuitry is directly connected to an oscilloscope. Using two channels of the oscilloscope, the signals from each gap of the probe are acquired to be processed by a personal computer.

In this work, we developed a probe with the same size and the same circuitry but changing the PCB by 3D printed elements (Fig. 3). The copper trace was substituted by a loop made of conductive PLA, 10 cm in diameter, 2 mm wide and 1 mm thick. To hold the conductive loop, the FR4 substrate was substituted by a 3D printed structure made of conventional non-conductive PLA. The bias current source was made on a conventional PCB and was glued to the PLA substrate. The same detector circuits as in [1] were used to connect the optical fibres to the oscilloscope.

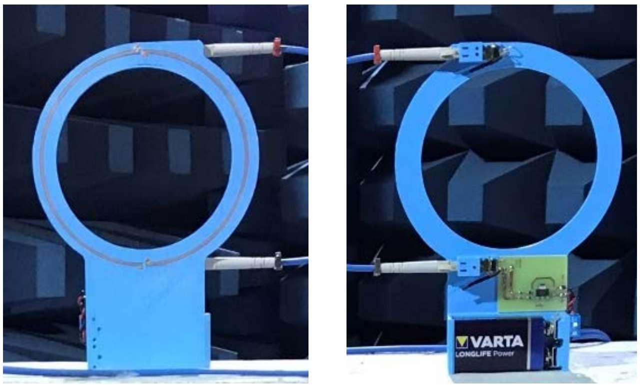

Fig. 3. 3D printed double-loaded loop probe.

B. 3D printing

The probe was built with the BQ Witbox 2 3D printer. The printing of the substrate (blue structure in Fig. 3) was done using the conventional process with 100 µm layer thicknes and 100 % infill. This part includes a clip for the battery and two sockets to house the lasers to connect the optical fibres (Fig. 4). The substrate has also a customized pocket so that the printed loop (brown trace in Fig. 3) can be fitted in.

The printing of the conductive loop is a more sensitive issue because the capabilities of the probe strongly depend on the electromagnetic characteristics of the filament.

Conductive PLA is a novel material, and its electrical characteristics are poorly specified. We used Electrifi Conductive 3D Printing Filament, which has a resistivity of 0.006 Ω/cm. However, the manufacturer does not specify how the properties of the material change with frequency. Moreover, the printing parameters such as the infill pattern and its density are also relevant, since they have been proved to have significant effects on the electromagnetic properties of the printed object [8]. We used a linear infill pattern with 100 % density in order to obtain a good homogeneity for the conductive loop.

Finally, the connection between the conductive printed trace and the electronic components was made using AA-DUCT 907 Silver Conductive Epoxy from Atom Adhesives, which has a resistivity of 0.0001 Ω/cm. Previous works showed that this adhesive was suitable to be used at radio frequencies [8]. The lasers to transmit the signals were connected to the printed loop using this method. The current source, which was built using a conventional PCB (Fig. 3, right) was connected to the loop by using the same conductive epoxy adhesive as well.

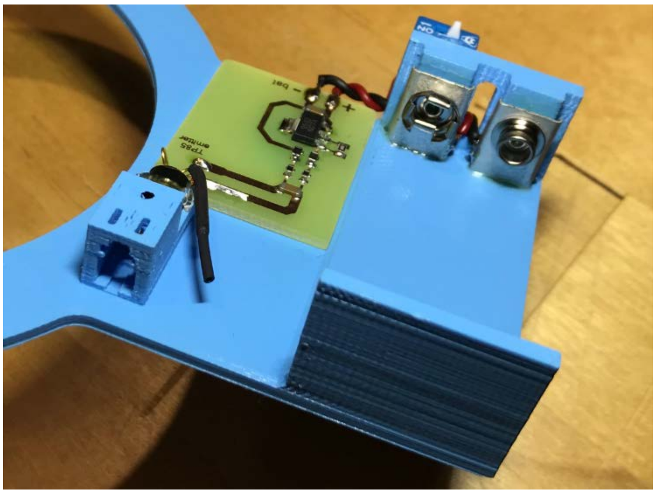

Fig. 4. Detail of the batery holder and one of the conectors for the fiber optic cable.

III. TEST SET UP FOR THE VALIDATION OF THE PROBE

The characterization was done inside a full anechoic chamber (FAC), by generating a calibrated E-field and its related orthogonal H-field, with the assumption of a plane wave. The FAC was previously calibrated using an Amplifier Research (AR) probe model FL7006, capable of measuring the three-axis E-field.

The plane wave was produced by an Electro-Metrics logperiodic antenna model LPA-30, connected to the output of an AR amplifier model AR150W1000 and a Rohde&Schwarz radiofrequency generator model SML03. The generator was set to produce a sinusoidal continuous wave with an amplitude of 10 V/m with its frequency ranging from 200 MHz to 1 GHz. The antenna was placed at a distance of 2 m from the probe and both polarizations, vertical and horizontal, were used. Fig. 5 shows a detail of this setup.

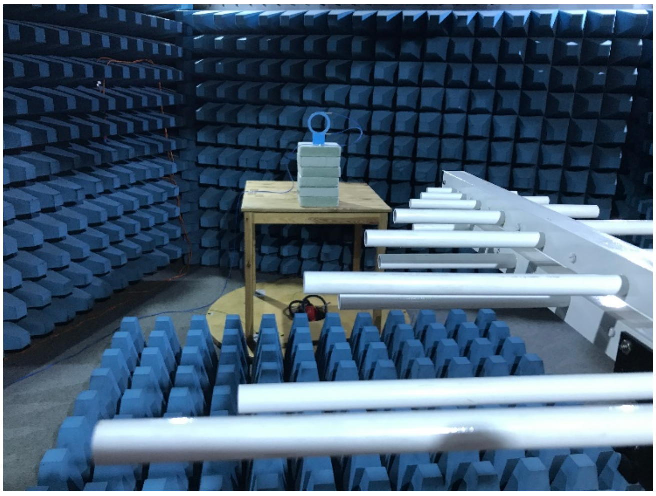

Fig. 5. Test set up in the anechoic chamber.

There are some positions of the probe that are best suitable to validate its response. The probe presented in [1] was testedin a position to receive the maximum electric field and the minimum magnetic field. In this work, we studied the same position plus the situation of minimum response to the electric field and maximum response to the magnetic field, and the situation of minimum response to both fields. In addition, we tested some more positions in order to obtain a more extensive set of data to be used in further studies to have a more detailed characterization. The additional collected data could be used, for instance, to calculate the reception diagram of the probe. Three basic positions for the probe (named A, B and C) were defined, as it is shown in Fig. 6 to Fig. 8. At position A, the probe was placed in a vertical position, with the loop facing the antenna, orthogonal to the propagation axis of the wave. Next, at position B, it was placed in a horizontal position, parallel to the floor. Finally, at position C, the probe was kept vertical with the loop parallel to the propagation axis. Each one of these 3 basic positions was tested 4 times, rotating the loop 90° around its centre to consider different directions of incidence. Each resulting position was tested for vertical and horizontal polarization which give a total of 24 situations.

IV. RESULTS AND DISCUSSION

Fig. 9 to Fig. 11 show the response of the probe at 300 MHz for positions A, B and C plotting both channels together. 300 MHz is a centered frequency in the bandwith of the probe presented in [1]. At this frequency, the loop is electrically small and a good performance is expected. This is why 300 MHz was consireded a convenient reference for this initial validation. From these results, the response related to the electric field can be calculated by subtracting both channels, while the response to the magnetic field can be obtained by its addition.

The results in Fig. 9 were obtained from the probe in a position of maximum reception of the E-field and minimum reception of the H-field (position A). Notice that the signals in Fig. 9 are in opposite phase. Thus, its subtraction gives a response with the maximum amplitude (maximum E-field), while its addition tends to a minimum amplitude (minimum H-field). It is clearly observed that the obtained response corresponds to a maximum reception of the E-Field and minimum H-field. These results are in accordance to the signals obtained with the PCB probe that were presented in [1], showing two sinusoidal waves in opposite phase for the maximum E-field and minimum H-field position.

Fig. 10 shows the signals from both channels when the probe is set for the maximum response to the magnetic field and minimum response to the electric field. Now, the signals are virtually in phase. In such a situation, its addition gives a result with maximum amplitude (maximum H-field), while both signals nearly cancel each other when subtracted (minimum E-field), which is in accordance to a maximum response to the magnetic field and minimum response to the electric field.

Fig. 11 plots the response when the probe is set for minimum coupling to both fields. The received signals differ by one order of magnitude from signals in Fig. 9 and Fig. 10.

In the case of a null magnetic field response, both signals in Fig. 9 should have the same amplitude and would cancel when subtracted. However, it can be observed that their amplitude is not the same. This gives a small but not null magnetic field response. Fig. 10 is analogous to Fig.9 for the

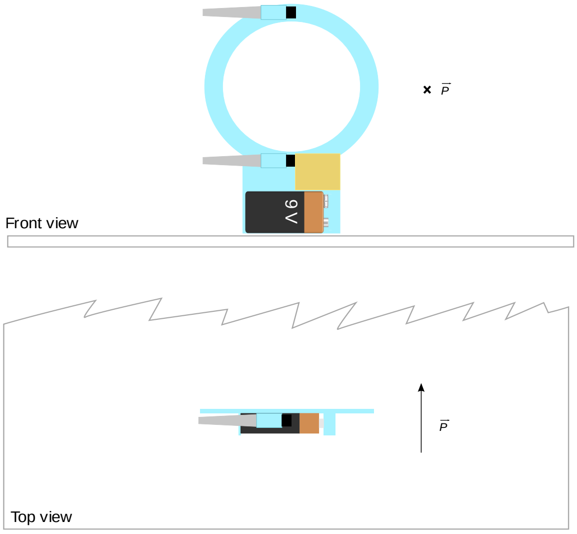

Fig. 6. Position A. The loop is vertical and orthogonal to the direction of propagation.

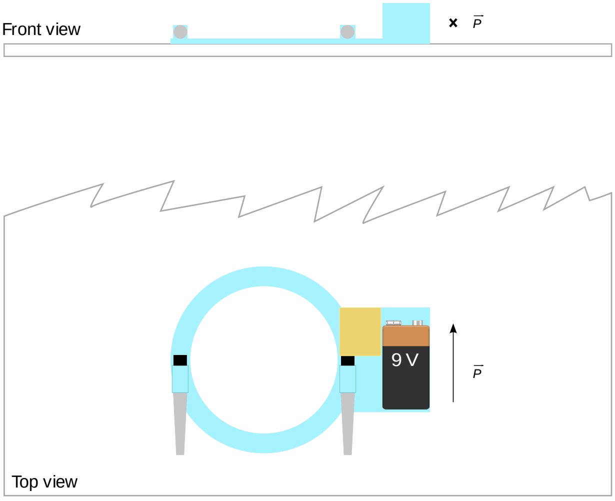

Fig. 7. Position B. The loop is horizontal and parallel to the direction of propagation.

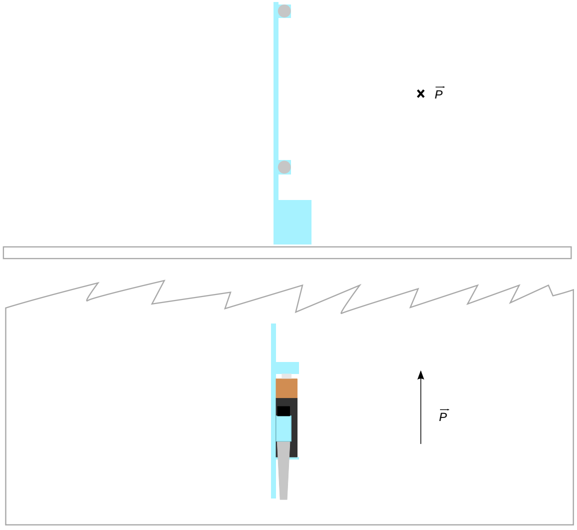

Fig. 8. Position C. The loop is vertical and parallel to the direction of propagation.

electric field, and the subtraction of both channels results in a small but not null electric field response. Several reasons can be argued for the difference in amplitude of the signals plotted in Fig. 9 and Fig. 10: The transmission losses for every optical channel are not paired, which yields to unmatched sensitivities since no gain or attenuation correction was applied. Additionally, the presence of the battery beside the loop, may distort the fields and lead to a non-plane wave incident upon the loop. Finally, the non-ideal response of the FAC may contribute to the difference in amplitude. If the generated wave is not perfectly plane, there may be an orthogonal component of the H-field that would contribute to the measurement. The FAC was calibrated by measuring the E-field inside the test volume, with the assumption that the H-field was orthogonal.

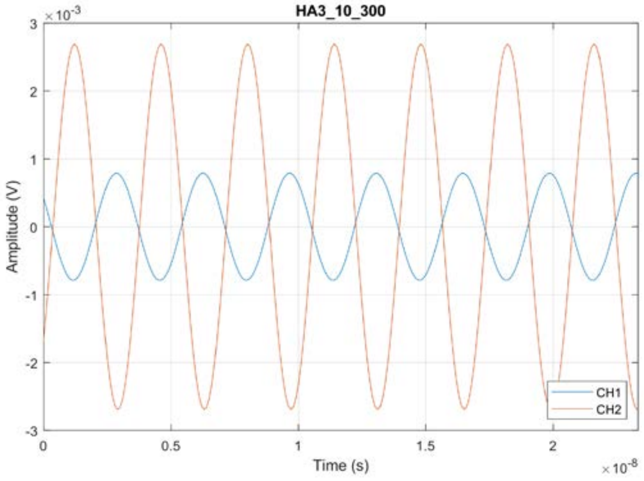

Fig. 9. Signals on both channels for maximum E-field and minimum H-field responses (position A, horizontal polarisation).

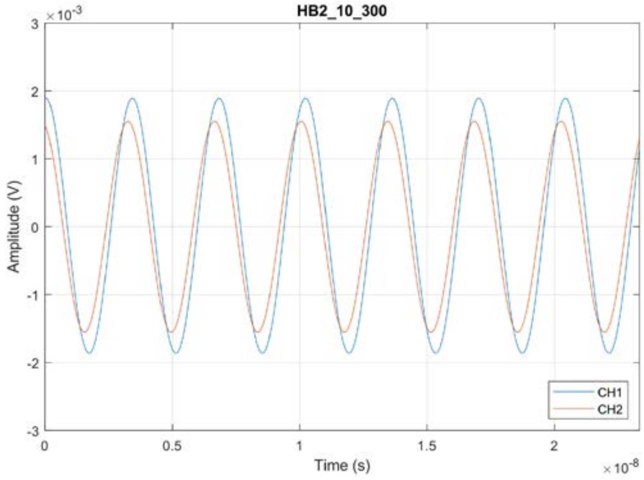

Fig. 10. Signals on both channels for minimum E-field and maximum H-field responses (position B, horizontal polarisation).

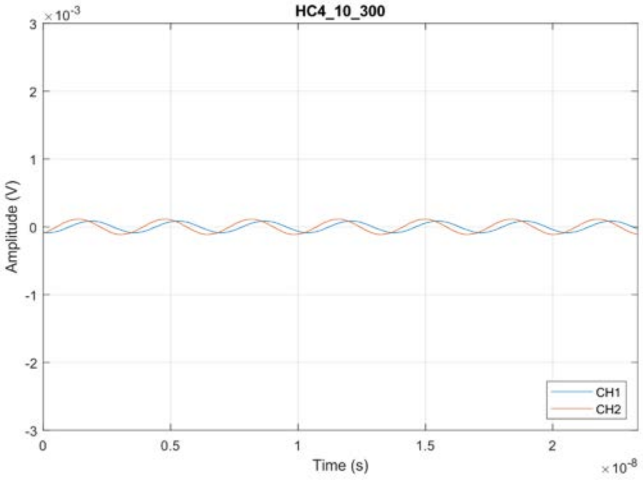

Fig. 11. Signals on both channels for minimum E-field and minimum H-field responses (position C, horizontal polarisation).

Despite the differences in amplitude, that can be explained and corrected in future works, the results let us validate the behaviour of the printed probe and consider the use of conductive PLA to build near-field probes. To have a detailed characterization of its response or a calibration, a more exhaustive procedure is needed.

V. CONCLUSION

Using 3D printing with conductive PLA filament to build a near-field probe has been proved to be feasible. This result is an excellent initial step to use this promising technique to develop tailor-made near-field probes for specific applications. Therefore, further study on this topic is justified. Future works should include the processing of the collected data to obtain the sensitivity pattern of the probe, and a more detailed calibration to obtain the sensitivity factors for the E-field and the H-field. In addition, the effects of the dielectric substrate and the detailed influence of the electromagnetic properties of the conductive material should be studied in deep. Finally, the electromagnetic characterization of the 3D printed objects is necessary to model the performance of printed probes during the design process.

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