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On The Use of Bio-sourced Substrate to Realize High Performance and Low Environmental Impact RF Components

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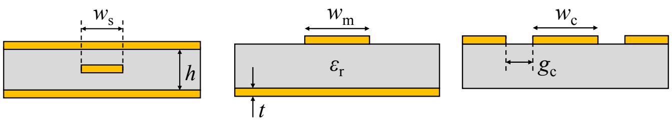
***Abstract* — This paper discusses the use of bio-sourced substrate for the realization of high performance and low environmental impact RF components. From a theoretical study on loss contribution and impedance variation for different TEM and quasi-TEM mode transmission lines, the potential candidate will be discussed in details regarding its pros and cons. For demonstration, the composite PLA/flax fiber is used to realize an isolated power divider/combiner with a 10 dB bandwidth (isolation, return loss) of 19.1% at the center frequency of 5.77 GHz together with a minimum insertion loss of 4.28 dB (including CPW to end launch transitions loss and transmission line loss). This study gives an initial approach for the realization of future eco-friendly RF systems.**

***Keywords* — biobased, bio sourced, isolation, PLA, power combiner, power divider.**

I. INTRODUCTION

Nowadays, most of the RF components and systems use conventional substrates, in particular glass fiber based, made of non-renewable fossil resources, and therefore have a high environmental impact during the whole life cycle from raw material extraction to fabrication till their disposal at the end of life as E waste. Through life cycle analysis (LCA) [1], the contribution of conventional FR 4 PCB to the total environmental impact can vary up to 40%. In this socio ecological context, interest has been increasingly rising towards the implementation of bio-sourced materials as an alternative solution for conventional substrates. Trade-off between carbon footprint and performance can be observed with microstrip patch antennas at 5.5 GHz made of Rogers RT5880, paper, and PLA (polylactic acid) substrates [2][3]. Through the studies in [2] and [3], high quality substrate from Rogers gives the best performance in term of antenna gain at the expense of the highest environmental impact (power and resources consumption, greenhouse gas, and toxic chemical products). The paper substrate presents the lowest environmental impact at the expense of lower gain. The PLA presents the compromise between Rogers and paper substrates.

To the author's best knowledge, the paper and/or (nano)cellulose-based substrates are the most common bio-sourced materials used in RF domain (especially in antenna design) thanks to their renewability and abundance [4][5]. The paper substrate presents its drawback regarding the high loss (loss tangent can vary up to 10-1), the sensitivity to moisture which can variate the substrate properties (permittivity and loss) and the flexibility as well.



(a) (b) (c)

Fig. 1. Studied transmission lines: (a) Stripline; (b) microstrip line; and (c) CPW

Recently, the use of PLA as RF substrate has got the attention from researchers to realize 3D printing RF components thanks to its lower loss (compared to paper substrate in counterpart), its rigidity, and its adaptability with actual 3D printing techniques [6]. To reinforce the conventional PLA substrate, a novel composite made of PLA and flame retardant flax fiber [7][8] has been exploited recently and it was proven to have promising RF characteristics (loss tangent varies from 0.02 to 0.08 from 900 MHz to 65 GHz compared to a maximum loss tangent of 0.12 in the case of paper substrate [7]). However, despite being a prominent candidate, this substrate may as well present some common bio-sourced materials drawbacks such as higher loss compared to conventional Rogers substrates and RF characteristics that are sensitive to humidity with a hysteresis behavior [8]. These flaws would result in a degraded performance for the bio-based components compared to the FR 4 and Rogers based ones if the design wasn't adapted to minimize their effect.

The aim of this paper is then to study the potential candidate to realize transmission lines using bio-sourced substrates with the objective of minimizing both loss and environmental impact.

Different TEM and quasi-TEM transmission lines are studied to evaluate the impact of bio sourced substrate to the loss contributions, including stripline, microstrip line, and coplanar waveguide (CPW). The quasi-TEM and TEM modes are preferred thanks to the unique definition of characteristic impedances (power voltage, power current, and voltage current), which facilitates the integration with other components. Furthermore, the quasi-TEM and TEM modes supports wider mono mode bandwidth and lower modal dispersion, compared to the TE, TM, or EH/HE modes [9].

For demonstration, the best candidate will be selected to realize an isolated power divider/combiner implemented with distributed resistors using PLA/flax fiber substrate.

This paper is organized as follows, section II presents the theoretical study for different TEM and quasi-TEM transmission lines implemented with the bio-sourced substrate in order to identify the best candidate that presents the best trade-off in terms of loss and sensitivity to moisture. Section III.

II. TEM AND QUASI-TEM TRANSMISSION LINES IMPLEMENTED ON BIO-SOURCED SUBSTRATES

A. Loss Contribution

Three common planar transmission lines are studied in this paper including stripline (TEM), microstrip line (quasi-TEM) and CPW (quasi-TEM) as topologies shown in Fig. 1, where w_s, w_m, and w_c correspond to the widths of the center conductor of the stripline, the microstip line, and the CPW, respectively; t is the thickness of the conductors, g_c represents the gap between the center and outer conductors of the CPW, h is the thickness of the substrate, and ε_r is the substrate relative permittivity.

Loss contributions are studied with different characteristics impedances from 30Ω to 100Ω. For this study, the composite PLA / flax fiber with $\varepsilon_r = 2.8$, $\tan\delta = 0.04$, $h = 1.6$ mm, and copper ($\sigma = 5.8 \times 10^7$ (S/m) and $t = 35\mu$m is selected. It is worth noting that the relative impact of the metalization of this substrate is similar to that of non-biosourced conventional substrates (cf. [1] [10] for more details about the substrate). The studied transmission lines' parameters are shown in Table 1.

Table 1. Parameters of stripline, microstrip line, and CPW.

Param. / Z_0	w_s (mm)	w_m (mm)	w_c (mm)	g_c (mm)
30Ω	2.29	8.69	8.69	0.03
50Ω	1.097	4.25	4.25	0.23
70Ω	0.58	2.422	2.422	0.476
100Ω	0.254	1.153	1.153	0.74

The strip width w_c of the CPW is fixed to be the same as that of the microstrip line. The radiation loss is ignored in this study since there is no discontinuity along the transmission line and the strip width is smaller than the guided wavelength. Therefore, the total loss is $\alpha_{total} = \alpha_c + \alpha_d$, where α_c and α_d are the ohmic and dielectric loss, respectively. In this study, the effect of surface roughness is ignored. However, it should be noted that the surface roughness adds an additional loss to the ohmic loss.

The loss contributions and total loss were analyzed using analytical equations in [11] and [12] and the results are shown in Fig. 2 and Fig. 3, respectively. It can be observed from Fig. 2 that the CPW structure presents the lowest dielectric loss α_d compared to the stripline and microstrip line. The stripline, in counterpart, present the highest dielectric loss due to the concentration of the energy inside the lossy substrate. It can be also observed from Fig. 2 that the dielectric loss is the dominant factor compared to the ohmic loss. The ohmic loss of the CPW becomes smaller for higher characteristic impedances. Therefore, the impact of surface roughness at higher impedance transmission lines will be smaller for CPW.

From Fig. 3, it can be noted that the CPW presents the lowest total loss compared to the stripline and microstrip lines with a wide range of impedance from 30Ω to 100Ω.

Although this study is realized for the PLA, the results can be applied to other bio-sourced substrates for example, the paper substrate, since the loss tangent in bio-sourced substrates is usually high and the dielectric loss is the dominant factor.

It's also important to note that, the width of the center strip in CPW is the same as the microstrip line, i.e., it requires less amount of metal for fabrication (microstrip line requires more metal to form a complete ground plane). This further reduces the environmental impact of the CPW with respect to a microstrip structure of the same strip width. Of course, the reduction of metal depends on the gap g_c in CPW.

From Fig. 2, Fig. 3, and Table 1, it can be observed that the CPW presents more advantages with the increase of characteristic impedances.

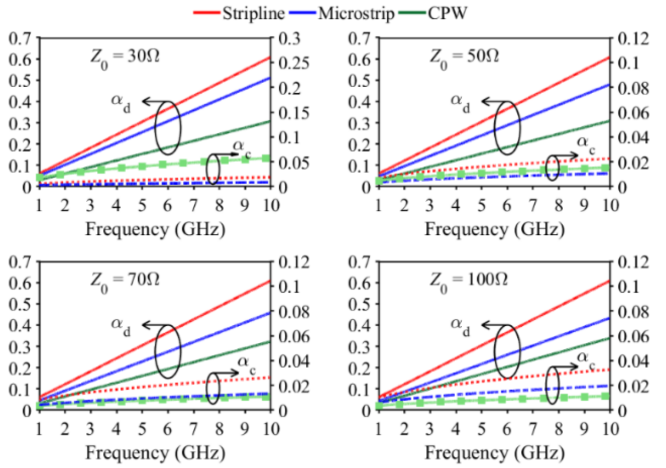


Fig. 2. Dielectric loss αd (dB/cm) and ohmic loss αc (dB/cm) in stripline, microstrip line, and CPW with characteristic impedances from 30Ω to 100Ω.

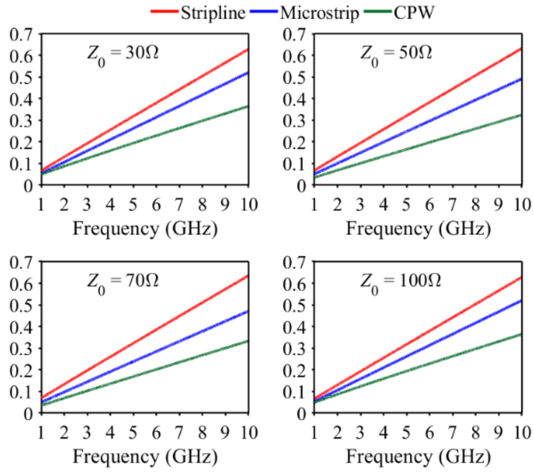


Fig. 3. Total loss αtotal (dB/cm) in stripline, microstrip line, and CPW with characteristic impedances from 30Ω to 100Ω.

B. *Impedance Sensitivity*

As was illustrated in [8], moisture can change the relative permittivity of the employed PLA substrate, which, for the same physical dimensions, reflects on the characteristic impedance. This section aims to compare the sensitivity of the characteristic impedance of the studied TEM and quasi-TEM transmission lines to the variation of the relative permittivity.

With TEM or quasi-TEM mode, the characteristic impedance could be considered as a constant at a given permittivity. Fig. 4 shows the variation of the characteristic impedances along with the relative permittivity that was set to vary from 2.5 to 3.5 (which covers most of the actual bio sourced substrates, including PLA and paper). It can be seen that the characteristic impedance of the CPW varies less rapidly than that of the stripline and the microstrip with respect to the variation of relative permittivity.

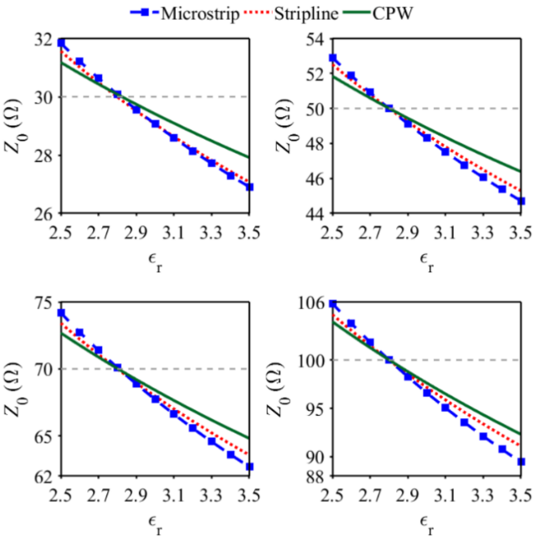


Fig. 4. Sensitivity of characteristic impedance Z0 in function of substrate permittivity.

It is now obvious from the studies conducted in this section that the CPW shows its superiority over the stripline and the microstrip line in terms of loss, environmental impact, and sensitivity to moisture. Furthermore, CPW has advantages in terms of simple integration with COTS components and signal isolation thanks to the ground planes around the signal part [13]. Therefore, CPW could be a good candidate for integration applications. However, the main drawback of the CPW is the existence of the odd- and even-modes. Depending on the design objective, one mode should be maintained while the other mode should be suppressed. So far, the even-mode is usually used since the odd mode could lead to high radiation loss [14]. However, in antenna application, the odd mode could be used [15].

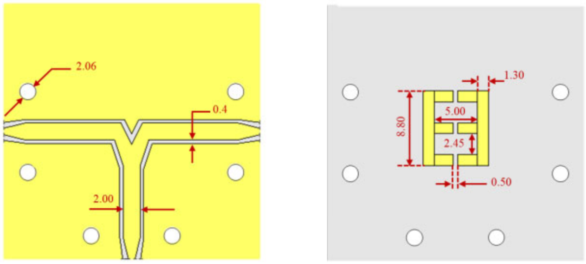
III. PLA CPW POWER DIVIDER/COMBINER

In this paper, a power divider/combiner will be demonstrated. Therefore, the even mode will be used. A common way to supress the odd mode is to use air-bridge to maintain the same potential at the two ground planes [16]. However, the use of air-bridge leads to a non-planar structure. Alternative ways to suppress the odd mode in planar form is to use strip-load where the potential is kept by electromagnetic coupling [13] or to use velocity compensation [14]. The strip load will be used in this paper.

For demonstration, a 70Ω CPW power divider/combiner was designed on the PLA/flax substrate ($\varepsilon_r = 2.8$, $\tan\delta = 0.04$, $h = 1.6$ mm) and simulated by CST Microwave Studio. The designed combiner and its relevant dimensions are shown in Fig. 5.

The 70Ω impedance is selected in the perspective of integrating with planar antenna such as half-wave dipole, which has characteristic impedances close to 70Ω. Furthermore, the impedance characteristics are maintained the same for all ports to facilitate the design of matching network when integrating with other components.

At the inputs, the end launch keeps the two ground planes at the same level of potential, therefore, the even mode is dominant. At the discontinuity (junction), since the velocities of odd and even mode are different, the odd mode can occur [14]. Therefore, loaded strip are added closed to this discontinuity. A network of three resistors is used to absorb the energy coupling to the strip. The use of resistor network is expected to increase the power handling capability limited by the rated power of a single resistor.

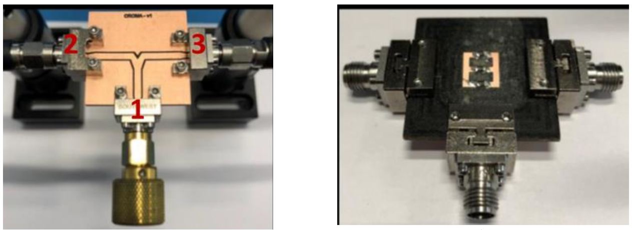


(*a*) (*b*)

Fig. 5. CPW power divider/combiner implemented on PLA/flax fiber substrate: (a) top layer; and (b) bottom layer. (Dimensions are shown in millimeter)

The fabricated prototype is shown in Fig. 6. For measurement, an SOLT calibration kit was used to move the reference plans to the input of the end launch connectors. A 50Ω broadband load was used to terminate the unused port (Fig. 6(*c*)). Tapered transitions from CPW to end launch connector are used for measurement. A back-to-back transition was simulated to evaluate additional loss caused by CPW to end launch transitions. The obtained return loss is lower than -14.6 dB from 4 to 8 GHz.

The simulated and measured *S*-parameters of the proposed CPW power divider/combiner are shown in Fig. 7 and Fig. 8 where good agreements could be observed. The differences between simulation and measurement are due to the parasitic effect of resistors that are not considered in simulation and the non-homogeneous of the flax fiber distribution as well. The measured minimum insertion loss is 4.28 dB at 5.36 GHz, including loss due to transitions from CPW to end launch connectors and the loss of CPW transmission line itself. At 5.36 GHz, the CPW presented in Fig. 5 has a theoretical total loss of about 0.19 dB/cm [12] and additional loss caused by transitions is evaluated in simulation to be about 0.23 dB.



(a) (b)

Fig. 6. Fabricated prototype: (a) measurement setup; and (b) bottom layer after mounting resistors.

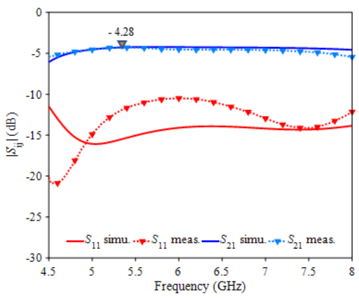


Fig. 7. Simulated and measured return loss |S11| and insertion loss |S21|.

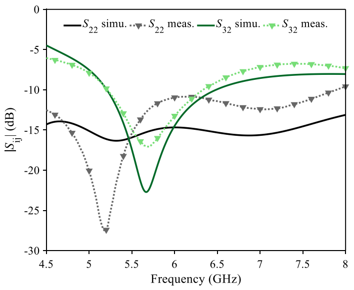


Fig. 8. Simulated and measured return loss |S22| and isolation |S32|.

In the measured frequency band (4.5 GHz to 8 GHz), all ports are adapted (S_{11}, S_{22}, and S_{33} are lower than -10 dB). The -10 dB bandwidth of isolation S_{32} is obtained from 5.22 GHz to 6.32 GHz (19.1% at the center frequency of 5.77 GHz).

IV. CONCLUSION

In this paper, a study on common TEM and quasi-TEM transmission lines was conducted to highlight the best topology (CPW) to be implemented on bio-sourced substrates in terms of losses, sensitivity to moisture, and environmental impact. An isolated power divider/combiner was implemented on PLA/flax fiber based substrate as a proof of concept. The suppression of the CPW's odd mode at the junction discontinuity was made by the addition of floating microstrip lines and an isolation network of three resistors. The obtained power divider/combiner has a -10 dB bandwidth (return loss and isolation) of 19.1% centered at 5.77 GHz together with a minimum insertion loss of 4.28 dB. This work gives a transmission line approach to design RF components and systems using bio-sourced substrate.

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