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THz POWER DIVIDER CIRCUITS ON PLANAR GOUBAU LINES (PGLs)

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Abstract—Terahertz spectroscopy is a new tool for real time biological analysis. Unfortunately, investigations on aqueous solutions remain difficult and need to work on nanovolumes. Integrated Terahertz instrumentation remains a challenge. We demonstrate that Planar Goubau Line (PGL) technology could bring a real practical solution to reach this goal. This study provides the design, fabrication and test results of passive PGL components like loads and power divider. These PGL components are designed, simulated, fabricated and measured with a Vectorial network analyser (VNA). Simulation and test data support PGL component designs. PGL components operate over a wide frequency range from 0.06 to 0.325 THz.

1. INTRODUCTION

The characterization of interactions on living matter is becoming an important goal, not only for biological analysis or clinical applications, but also for environment or biological security in food processing. Current analyses are made by invasive methods with strong drawbacks. Principal ones are probably the alteration of the biological activity by chemical reactions or by fluorescent tags bonded on molecules. Millimeter waves (MW) and Terahertz (THz) spectroscopy could bring interesting solutions in this field [1, 2]. Most THz spectroscopy

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techniques use a free space propagation mode [3]. Unfortunately, biologists are interested by investigations on liquid aqueous solutions where measurements are difficult due to the strong absorption of THz waves. Original solutions could be brought by microfluidic technology if passive THz circuits can be integrated in microdevices [4, 5]. We have suggested to use propagation structures in PGL topology [6]. Similar to the microstrip line, coplanar waveguide (CPW) or coplanar strip line (CPS) at respectively microwave, millimeter wave and sub-THz frequency regions, planar Goubau lines are well matched for passive THz circuits [7]. We have already demonstrated that the propagation on nanometric metallic wires is possible with good propagation characteristics [8]. Here, we define the first elements for the design of complete integrated THz instrumentation, such as six-port THz reflectometers. Six-port circuits find wide-spread applications in microwave instrumentation and six-port wave radio digital communications [9]. However, the realization of six port circuits in the THz frequency range remains a challenge. This paper describes the characteristics of two passive components: a power divider and a PGL matched load which are the basic building block of a future integrated THz six-port reflectometer.

2. PLANAR GOUBAU LINE ON SUBSTRATES

The propagation around a wire coated with a dielectric has been described by Goubau in 1950's [10]. More recently, same results are obtained with rectangular thin conductors deposited on dielectric substrates, named planar Goubau lines (PGL) [11]. These new PGL lines can be used for the design of passive THz circuits. In present case, measurements are performed with Vectorial Network Analyzers (VNA) up to 0.325 THz using on wafer probe station with coplanar tips. They are realized with Agilent 8510XF VNA from 0.045 to 0.110 THz range and Anritsu 37147C VNA associated with a frequency multiplier to work on 0.14–0.22 THz and 0.22–0.325 THz range. The calibration use a standard LRM calKit of Cascade Microtech for XF range and a CS15 of Picoprobe for 0.14 to 0.325 THz analysers. We have already studied coplanar waveguide-PGL transitions with a high excitation efficiency close to 75% [12]. It is known that coplanar lines easily excites substrate modes if ground plane widths are not judiciously chosen. The PGL propagation mode requires the use of a bulk substrate but, unfortunately, thick substrates contribute to the excitation of unwanted substrate modes. Using membrane is possible, but the technological realization is difficult with a future microsystem integration. Nevertheless, a compromise in the choice

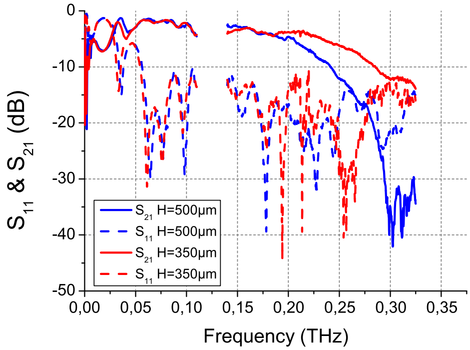


Figure 1. Experimental transmission and reflection parameters obtained with PGL realized on two Pyrex substrates with thicknesses $h = 500\,\mu\text{m}$ and $h = 350\,\mu\text{m}$.

of substrate thickness can be found. Reducing the thickness of the substrate increases the cutoff frequency of unwanted modes. We measured the $[S]$ parameters on structures with two different substrate thicknesses: 500 µm and 350 µm. We used a glass substrate (Pyrex) with parameters $\varepsilon_r = 3.75$ and $\tan\delta = 0.008$. Each test structure is composed of two CPW-PGL transitions linked with a 1.5 mm-long and 5 µm-wide wire realized in Ti/Au metallization (500/4500 A). Figure 1 clearly shows the influence of different substrate thicknesses at higher frequencies. The analysis of these curves shows i) the cut-off frequency of the transitions at 0.06 THz, and ii) the influence of the substrate on the performances at higher frequencies.

The unwanted substrate modes are mainly excited by the CPW/PGL transition that acts as an antenna. One part of the field is propagated along the wire and the other part propagated inside the substrate. We can compare our substrate to a dielectric waveguide, so compute the cut-off frequency at -3 dB. In a first approximation, we can use the cut-off frequency relationship of a dielectric waveguide given by:

$$f_c = \frac{c}{2 \cdot \sqrt{\mu \cdot \varepsilon_r}} \sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{h}\right)^2} \tag{1}$$

with f_c the cut-off frequency, a the Goubau line excitation width described in [12] ($a = 1200\,\mu\text{m}$), h the thickness, and ε_r the permittivity of the dielectric substrate. Figure 2(a) presents the f_c evolution with the substrate thicknesses h. The cut-off frequencies of our two substrate thicknesses are $f_c = 0.168$ THz for $h = 500\,\mu\text{m}$

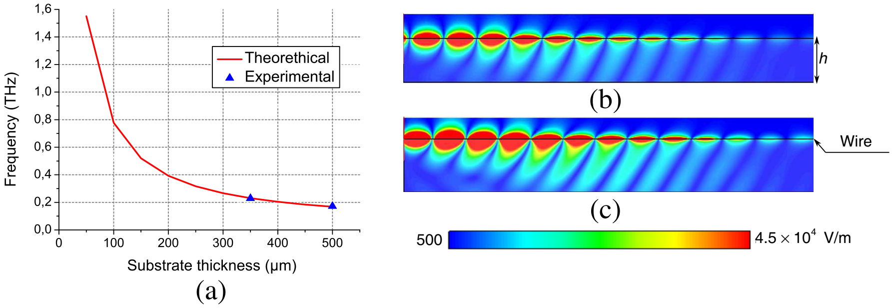


Figure 2. Evolution of the cut-off frequency of the substrate modes with (a) the substrate thickness and the electric field magnitude inside two substrates: thickness of (b) 350 µm and (c) 500 µm at a frequency of 0.28 THz.

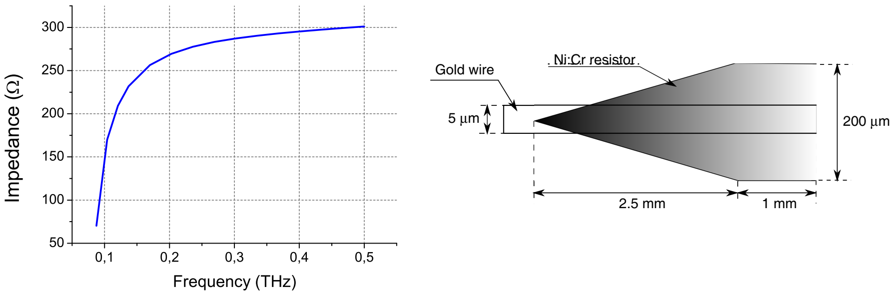
and $f_c = 0.230$ THz for $h = 350$ µm. The measurements yield $f_c = 0.172$ THz and $f_c = 0.228$ THz respectively. Our simple model gives us a good approximation of the experimental measurements (Figure 2). We show in Figure 2 the electric field along a wire with $h = 500$ µm (Figure 2(b)) and $h = 350$ µm (Figure 2(c)) where h is the dielectric substrate thickness.

We can say that substrate modes are a key point for high quality THz propagation in PGLs. In the future, passive THz structure should be designed with smaller transitions and thinner substrates.

3. MATCHED LOAD

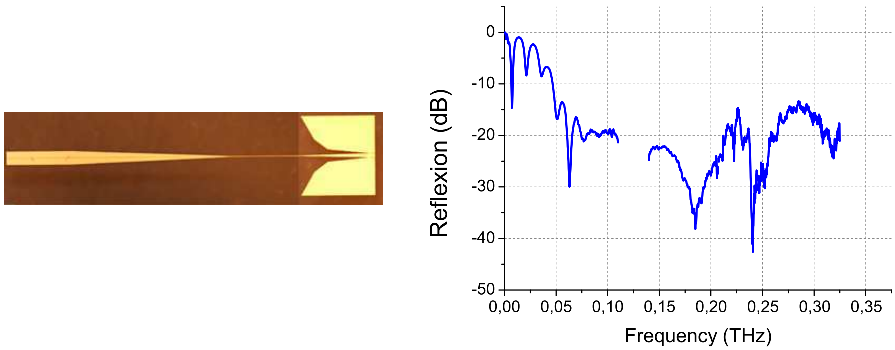
The first components that we have studied are PGL loads. We have estimated the wave impedance of a single PGL by simulation. We report in Figure 3(a) an example of the evolution of the wave impedance of a PGL versus the operating frequency. The wave impedance of a 5 µm-wide wire is 280 Ω in the frequency range of interest. Figure 3(b) shows the scheme of the load based on a lossy line. It is composed of a Ni : Cr 90 : 10 high value resistor below the PGL line.

We have developed the matched load by pulverization (Figure 4(a)). Its resistivity is $7.06 \cdot 10^{-7}$ Ω/m. The characterization of this structure in terms of reflection parameter is less than -15 dB at all frequencies greater than 0.06 THz (Figure 4(b)).



(a) (b)

Figure 3. (a) Evolution of the wave impedance of a 5 µm-wide PGL and (b) design of the matched load with a high resistance lossy line.

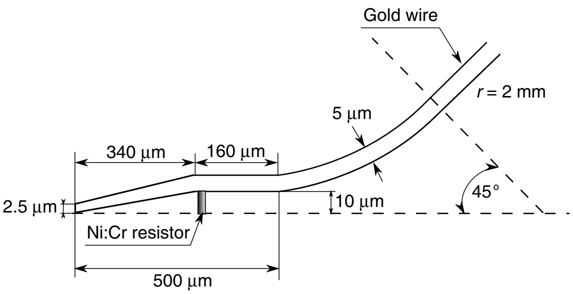


(a) (b)

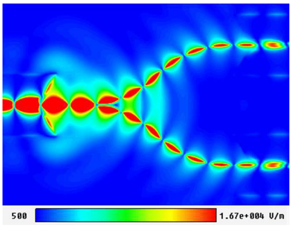
Figure 4. (a) Realization of the matched load. (b) Reflection parameter of a matched load described in Figure 3(b).

4. POWER DIVIDER

One of the basic components for the design of complex passive circuits, such as six port circuits, is the design of power dividers. In a first approach, we have chosen the same topology as a Wilkinson power divider in millimeter frequency range. We simulate a PGL power divider structure with two output wire sections. To minimize the coupling between the two branches of the power divider, we provide a local high resistance near to twice the line impedance of the wire. For simplicity, Figure 5(a) shows the half of the power divider configuration only. The entire configuration of the power divider is symmetric with respect to the horizontal broken line. Figure 5(b) shows the electric field split along two wire sections at 0.18 THz.

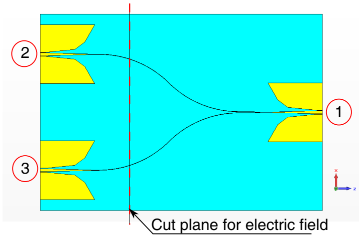


(a)

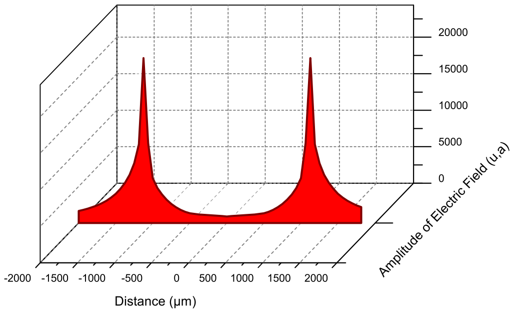


(b)

Figure 5. (a) Scheme of the split of the PGL. (b) Repartition of the electric field along these two branches.



(a)



(b)

Figure 6. (a) Scheme of the power divider structure. (b) Amplitude of the electric field around the wires of 5 μm width with an extension of 80 μm at half power.

Figure 6 shows the amplitude of the electric field at the wires vicinity at 0.18 THz. We see that we obtain a perfect symmetry of the electric field amplitude.

In a final step, we have integrated these two passive elements (load and power divider) together. We estimated the isolation resistance as follows:

$$R = \frac{\rho \cdot L}{W \cdot T} \tag{2}$$

with R the resistance of the layer, ρ the resistivity of metal, L and W the length and width, respectively, and T the thickness of metal. We used a metal film of Ni : Cr 90 : 10 of $T = 50\,\text{nm}$ thickness. This film gives a resistance of 14.1 Ω/square. We designed the resistive film with an area of $L = 20\,\mu\text{m}$ and $W = 2\,\mu\text{m}$. Figure 7 shows, in detail, the test jigs used for measurements of S_{11}, S_{21} and isolation S_{32} parameters with on circuit loads. The S_{32} parameter has not been measured in

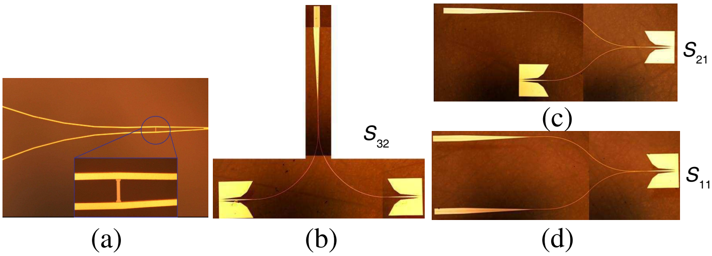


Figure 7. (a) Micrograph of the isolation resistor. (b), (c) and (d) Details of the experimental test jigs for S_{32}, S_{21} and S_{11} parameter measurement respectively.

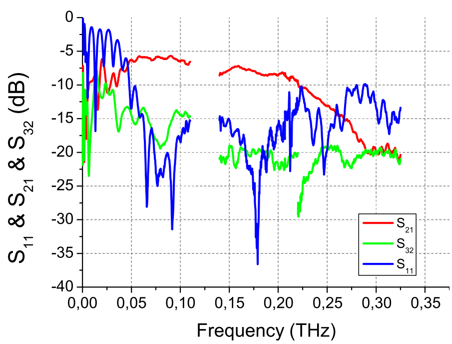
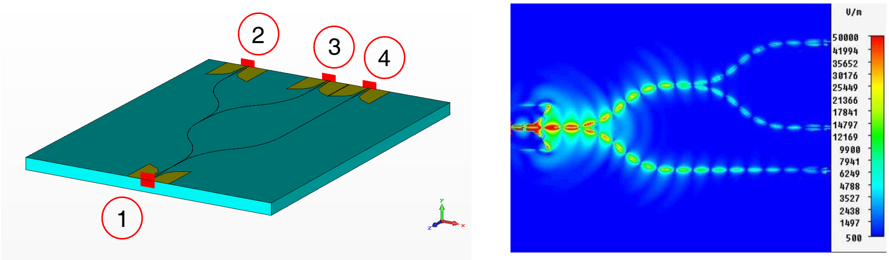


Figure 8. Measurement of S_{11M}, S_{21M} and S_{32M} parameters for power divider by 2.

the conventional configuration, because the measurement with tips on the vectorial Network Analyser needs the port of each side. It is the reason that we designed a specific test fixture described in Figure 7(b).

Figure 8 gives the measurement results of the previous parameters for the power divider. The transmission level for this structure is $S_{21} = -8.21$ dB at 0.18 THz. Each branch of the power divider is 3.64 mm-long. The Goubau line absorption $\alpha = 0.48$ dB/mm has been found by a Bianco Parodi method [13], and CPW/PGL transition losses have been estimated to 1.56 dB/transition. Thus, the transmission parameter of a 3.64 mm-long Goubau line with two transitions is $S_{21} = -4.87$ dB. $S_{21} = -8.21$ dB is the previous transmission divided by two (-3 dB). Actually, the difference between the two values is 3.34 dB. The 0.34 dB excess corresponds to additional losses due to Goubau lines bending in the power divider structure.

This divider can be extended to obtain a by-four divider. It is represented for ports 2 and 3 in Figure 9(a). Port 4 power is only



(a) (b)

Figure 9. (a) Scheme of the power divider structure by 4. (b) Repartition of the electric field along this structure.

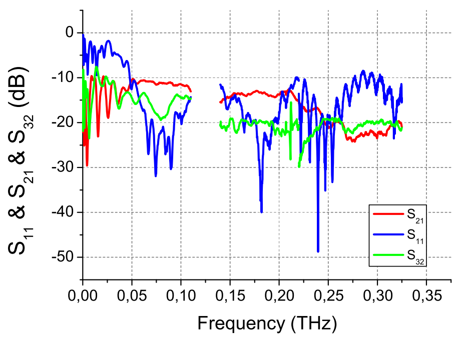


Figure 10. Measurement of S_{11M}, S_{21M} and S_{32M} parameters for power divider by 4.

divided by two in order to check the independence of the divided branches. Figure 9(b) shows the repartition of electric field along this structure.

Figure 10 shows the measurement results of S_{11M}, S_{21M} and S_{32M} parameters for the power divider. The transmission level for this structure is $S_{21} = -13.34\,\text{dB}$ at 0.18 THz. Branches are now 7.28 mm-long. With two transitions, a 7.28 mm-long Goubau line is characterized by $S_{21} = -6.61\,\text{dB}$. $S_{21} = -13.34\,\text{dB}$ corresponds to a division by four ($-6\,\text{dB}$), because of the 6.73 dB difference.

5. CONCLUSION

We have demonstrated that high quality passive PGL components can be designed at THz frequencies. One limitation of this technology is the substrate mode generation when the frequency range is increased.

We show that this limitation can be overcome by thinning down the substrate. For that, it is possible to use the microstructuration technique for the realization of membrane below the PGL. This membrane can also be realized in polymer or nitride-oxide layer. We have described the characteristics of two components: a matched load and a power divider. We have combined together these components to provide original function with very good results. The proposed component configuration gives us the first elements required to design a complete integrated terahertz reflectometer. The next challenge is the realization of a such integrated THz six-ports reflectometer.

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