Development of Substrate Integrated Passive Microwave Circuits

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ABSTRACT

In this work, the authors have developed a set of communication devices implemented in three different types of Substrate Integrated Circuit (SIC) technology: Decoupled Empty Substrate Integrated Waveguide (DESIW), Alternating Dielectric Substrate Integrated Waveguide (ADSIW) and Empty Substrate Integrated Coaxial Line (ESICL). The three are mixed technologies, waveguide-printed circuit, which perfectly solve the deficiencies associated with traditional technologies, integrating a rectangular waveguide or coaxial line into a planar substrate. With these novel hybrid technologies, traditional circuits can be implemented on a waveguide or coaxial guide but inheriting the advantages of the planar technologies, in terms of easy integration and low cost, as well as the advantages of waveguides and coaxial guides, in terms of low radiation losses. In addition, the practical implementation of these SIC lines and components has led to the efficient realization of broadband transitions with planar circuits, in order to get the integration with the same substrate and to use low cost planar production techniques.

The developed devices allow the use of substrate sections with different permittivity, even susceptible to being variable due to the use of a material whose dielectric permittivity varies with a polarization voltage, such as the liquid crystal. This provides a simple mechanism for the tuning of the device response after its manufacture. In this way, the same device can be used for a wide range of applications at different frequencies.

Keywords: liquid crystal, substrate-integrated circuits, reconfiguration, high-frequency communication, passive microwave devices.

1.- INTRODUCTION

The growing expansion of multimedia applications, satellite communication systems and wireless communication systems have prompted the electronics industry to operate in new frequency bands with a sufficient spectrum [1]. In addition, they have promoted the need to have low-cost technologies, with high performance, and that are adequately fitted to the requirements of mass production, while also allowing a significant reduction in the volume, weight and consumption of telecommunications equipment. Moreover, it is increasingly required that the communication devices are reconfigurable, that is to say that the same device can work dynamically in different frequency bands, adapting its response to the conditions of the environment, by means of mechanical, electronic or electromagnetic processes [2]. To achieve this, systems must incorporate devices or materials that allow varying some of their physical characteristics depending on: voltage, magnetic field, temperature and/or applied pressure.

Some examples of elements with this kind of dynamic behavior are ferrites [3], [4], [5], PIN diode [6], varactors [7], RF MEMS [8] and ferrolectric materials such as Barium-Strontium-titanate (BST) [9], KTa0.45Nb0.55O3 (KTN) [10] and liquid crystal [11].

The characterization of the electromagnetic properties of the liquid crystal is a field of study of high interest for the industry. These materials present different permittivities and losses depending on their polarization states, so their measurement is not trivial. There are previous works about characterization of liquid crystals at high frequency (upper K-band) and of course in the optical spectrum, but there are hardly any studies in lower bands, C-band or X-band, which are of great interest in current communications [12]-[17].

This type of materials are used to implement numerous devices, such as phase shifters, resonators and filters. These devices are implemented on transmission lines, which allow to guide the electromagnetic wave. Despite the fact that there are several implementation technologies, its commercial success demands a great efficiency in terms of cost and mass production along with the electromagnetic guidance features. Waveguide is the classical technology, which provides excellent performance: total electromagnetic shielding (it eliminates radiation loss totally), reduced insertion loss, ability to carry high power signals and high quality factor. Nevertheless this technology does not lend itself to mass production, since it requires a great deal of assembly and operation effort. In addition, this solution is, in general, bulky, heavy and difficult to integrate with other high-frequency integrated circuits, which are manufactured today in planar technology.

The intrinsic advantages of planar devices are numerous: low cost, reduced weight, compact size and relatively simple, economical and precise manufacturing processes. However, planar circuits present high losses and a reduced quality factor. In order to overcome the deficiencies and limitations of current manufacturing technologies, a whole new generation of high-frequency integrated circuits, known as Substrate Integrated Circuits (SICs), has recently been developed. The foundation of the SIC circuits is to synthesize non-planar structures on a flat dielectric substrate.

Substrate Integrated Waveguide (SIW) [18] technology is a mixed technology, waveguide-printed circuit board, that integrates a rectangular waveguide on a flat substrate. This is an "artificial" waveguide, which is synthesized by means of two parallel rows of metallized step holes that unite two planar conductors separated by a dielectric substrate (that has a certain permittivity value and related losses).

The Empty Substrate Integrated Waveguide, or ESIW [19], is another step in the improvement initiated by the SIW technology. In this case, the sidewalls of the synthetized waveguide are continuous metal walls, and the dielectric substrate is removed from the waveguide propagation region. This allows to reduce the associated losses and increase the quality factor of the devices, but maintaining the advantages of low cost, easy manufacturing, and integration with planar circuits.

Finally, the Empty Substrate Integrated Coaxial Line Transition (ESICL) [20] enables the construction of an empty coaxial line within a substrate. This type of structure presents the advantage of having two conductors (a very attractive property when it is used for reconfiguration applications) on which a completely confined TEM mode is propagated, and therefore it is immune to external electromagnetic interference.

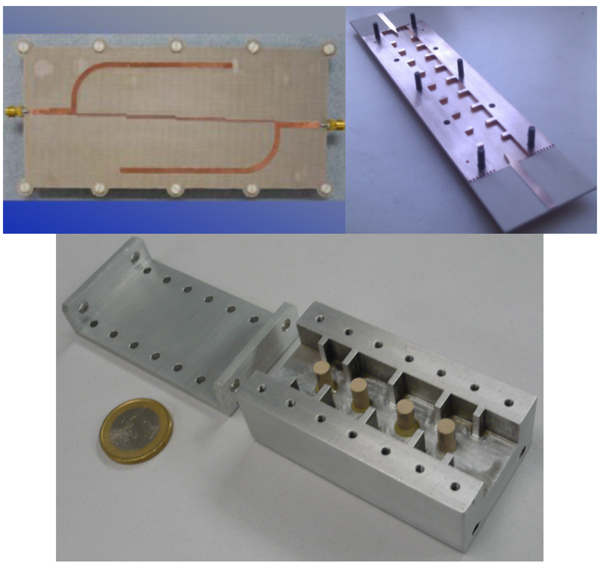

Figure 1. Microwave filters in microstrip (planar) technology, Empty Substrate Integrated Waveguide technology and waveguide technology.

2.- RESEARCH OBJECTIVE

The main objective of the research was the design and implementation of several microwave passive devices on substrate-integrated lines. The idea was to use SIC transmission lines, specifically the DESIW line, to implement a resonator, a filter and a phase shifter; moreover, the Alternating Dielectric SIW line was used to implement a filter, and the ESICL to implement a resonator, a phase shifter, a power divider and a directional coupler. Another aim was to study the potential variation of the response of these lines based on an external signal. In principle, and if the viability analysis enabled it, liquid crystals were used which, filling the interior of the device, allow their response to vary by changing their relative permittivity.

Since the considered transmission medium and the guided structures were slightly studied, the work had phases in which they had to be analyzed more deeply, as well as the problem of using these materials in the selected guided structure. On the other hand, any real process has a certain random behavior, so the effects of manufacturing tolerances on the final devices were also studied. This can help on the selection of one or other structure for future jobs.

3.- PROCEDURES AND TECHNIQUES

To achieve these high-level objectives, the following procedures and techniques were followed:

- **Study and analysis of ferroelectric materials.**

A detailed study of ferroelectric materials in general, and of liquid crystal in particular, was needed to know and characterize their properties and the necessary techniques for their implementation.

Since the electrical permittivity of the liquid crystals is proportional to the polarization of their particles with respect to the electromagnetic field that is applied to them, it was necessary to study the methods that exist for their polarization. This polarization field is applied to achieve a resting state (anchoring the liquid crystal in one of its limit states) and to serve as an actuator that allows to rotate its molecules.

On the other hand, the current research on the liquid crystal at microwave frequencies has increased the number of liquid crystal commercial mixtures, which require a study of their permittivity and loss in different polarization states.

For this study, a bibliographic collection and a research work on the measurement methods of these parameters was required. The measurements must be done at certain particular frequencies by using resonant cavities, as well as in a bandwidth by using waveguides and/or transmission lines.

This analysis was carried out in collaboration with two research groups of other Universities: the Department of Physics of Condensed Matter of the University of Zaragoza, and the High Frequency Laboratory of the Technical University of Cologne (THK).

- **Study of SIC guided structures.**

A study of the SIC structures in general, and of the structures DESIW, ADSIW and ESICL in particular, was required. This study began with the theoretical characterization of these structures, and the analysis and design of broadband transitions that enabled the easy implementation and measurement of devices. The study of the manufacturing techniques, necessary for their implementation, was also carried out, where it was necessary to employ simulation models that were faithful to reality.

- **Compatibility study.**

Once the guiding structure and filling material were studied, it was necessary to perform a compatibility study among them in order to ensure the correct development of the project. This compatibility was considered both theoretically and in practice, thus a relatively simple device (e.g. a resonator) was designed and manufactured to analyze it in an intuitive way.

This compatibility study had two main

objectives: the feasibility study of the project and its redesign in case of finding incompatibilities, as well as the election of the type and number of equipment that could be designed and manufactured.

On the other hand, it was necessary to study and design the polarization networks that allowed the RF signal and the polarization voltage to be properly uncoupled. Moreover, the study also considered the orientation of the liquid crystal particles by using alignment layers and/or an electric or magnetic field.

- **Device design**

Some devices were designed on DESIW: a resonator, a filter and a phase shifter; a filter on ADSIW and some others on ESICL: a resonator, a phase shifter, a power divider and a directional coupler. The designs were made for both reconfigurable and fixed devices, and the rest of the necessary elements for the correct functioning of the devices was also designed, such as alignment elements, polarization networks, etc. These designs were developed with in-house produced specific simulation and optimization software, and with commercial electromagnetic simulation software, such as CST Studio Suite.

- **Manufacture of designed devices.**

For manufacturing the prototypes of the designed devices, authors used the techniques and experience developed by the Group of Microwave Applications (GAM) of the iTEAM research institute of the Universitat Politècnica de València (UPV), and the Group of Applied Electromagnetism of the Universidad de Castilla la Mancha (UCLM). It was necessary to use a precision milling machine with numerical mechanical control and a laser milling machine for the fabrication of the devices. The reconfigurable components were filled with liquid crystal. For this reason, precise techniques were necessary for welding the structure, as well as the use of the pins of the polarization voltage and the necessary elements to isolate it of the high frequency signal. In Figures 2 and 3 we can see images of some of the manufacturing processes employed in this work.

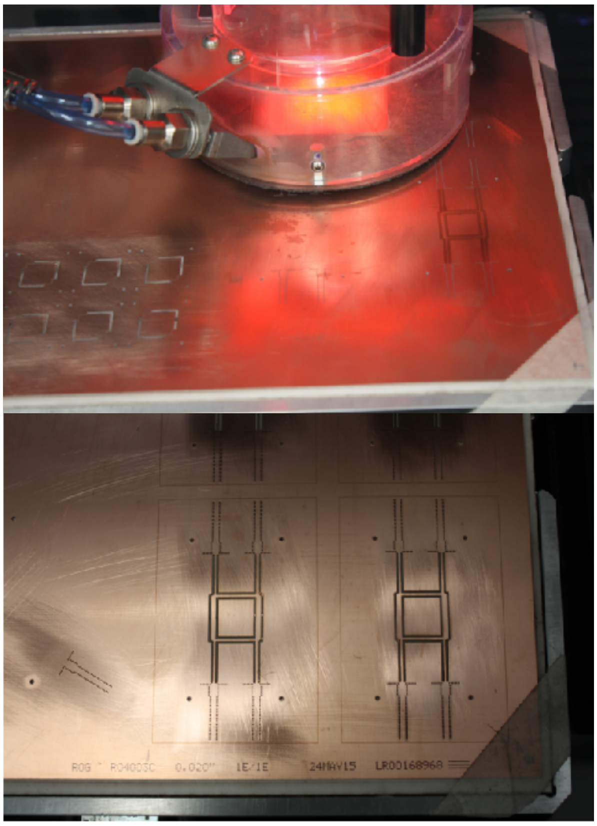

Figure 2. Manufacturing process by laser milling.

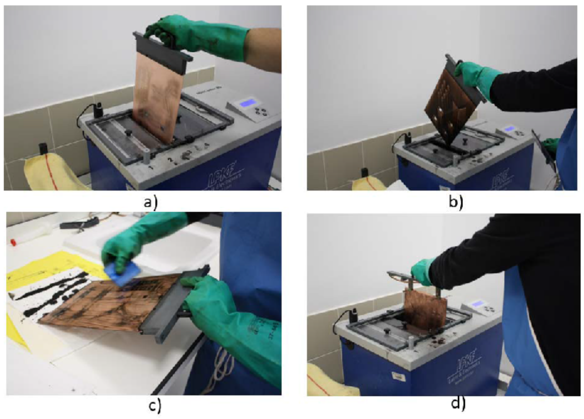

Figure 3. Galvanic plating of the device, a) immersion in the reactive solution, b) extraction, c) cleaning d) immersion in the acid solution.

ESICL and DESIW lines and transitions were designed, manufactured and measured. These lines were optimized to be filled with liquid crystal and therefore to have a reconfigurable response. These basic lines were used to manufacture other devices, such as filters, resonators, power dividers, phase shifters and hybrid couplers.

The liquid crystal was used to fill some of these devices. The process (see details in figures 4 and 5) was not so simple, and there were many considerations to take into account, because the liquid crystal needs to be perfectly confined and, additionally, it has to be possible to polarize it afterwards.

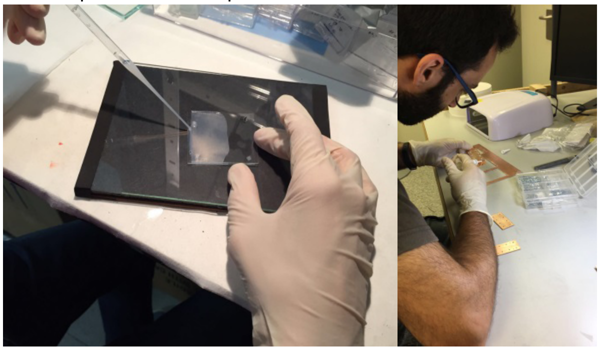

Figure 4. Filling of a glass cell and a microwave device with liquid crystal

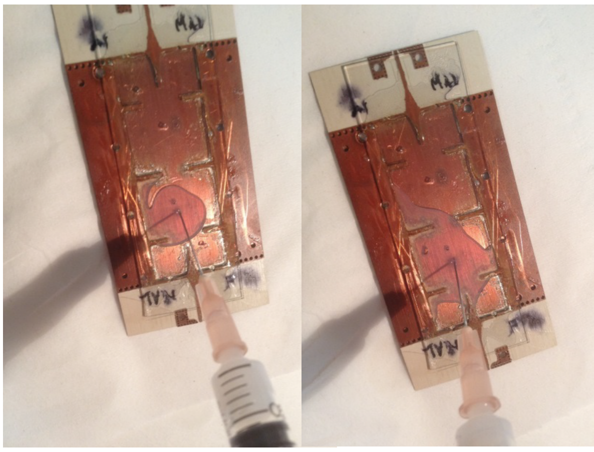

Figure 5. Detail of the filling process of a microwave filter with liquid crystal.

- **Reconfiguration and measurement**

Since there were some devices that were filled and some others that were not, the viability of implementing both kinds of responses (fixed and reconfigurable) was proven. The frequency responses were measured and compared to simulated results. The measurements were carried out with a vector network analyzer, obtaining the behavior of the device in a certain range of frequencies. The measurements required a calibration that considered the effects of the wires, but also of the connectors and the line sections that carry the signal to the device. For this purpose, specific TRL calibration kits were manufactured, for each technology and frequency range.

Moreover, the characterization of new liquid crystal mixtures was performed at microwave frequencies. Three cylindrical resonator cavities (at 5 GHz, 9 GHz and 11 GHz) were manufactured, and the electromagnetic responses of glass cells filled with the different mixtures of liquid crystal were measured. With these electromagnetic responses, it was possible to extract the permittivity and loss tangent of the considered mixtures. Some images of all these practical procedures are shown in Figures 6 and 7.

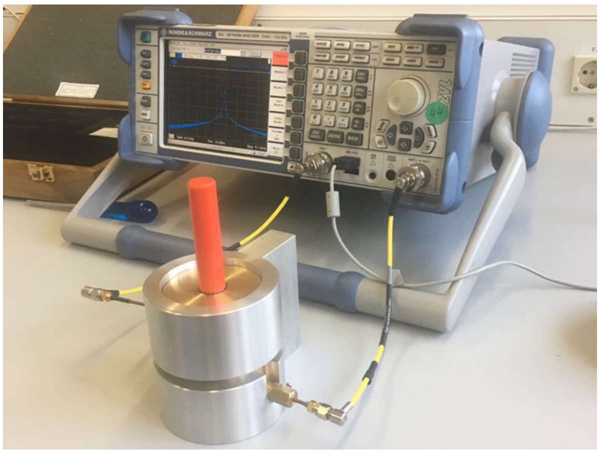

Figure 6. Electromagnetic characterization of liquid crystal mixtures.

Figure 7. Measurement of the frequency response of the devices. Calibration kit and measurement setup. Detail of the measurement process.

4.- RESULTS

The first developed device was an ADSIW filter at 11 GHz. This device is based on the ESIW technology, alternating sections of waveguide with and without dielectric. The structure combines resonant cavities and impedance inverters, which produces a directly coupled cavities H-plane filter. The filter is a single conductor structure, thus a polarization voltage cannot be applied for reconfiguration. Figure 8 presents the active layer and a detailed view of the sections of the manufactured ADSIW filter. The detailed view shows the discontinuity between SIW-ESIW sections and the sidewall conductors: metallized via holes for SIW and substrate metallization for ESIW. Figure 9 shows that the filter pass-band is 3% and the insertion loss is below 2.7 dB. Moreover, the out of band behaviour of the filter, i.e. the stopband, with attenuation higher than 35 dB, can reach values up to 20 GHz, which is around $2f_o$.

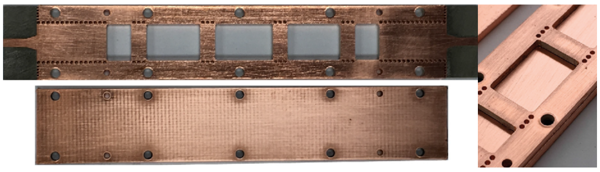

Figure 8. Filter built on Alternating Dielectric Substrate Integrated Waveguide (ADSIW) technology.

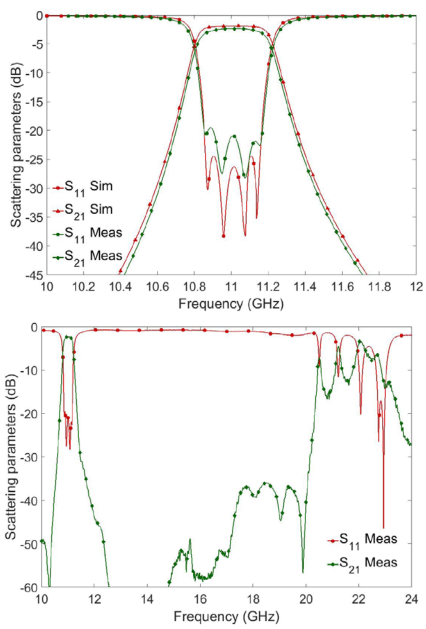

Figure 9. Comparison of measured and simulated frequency responses of ADSIW filter.

The natural improvement of ESIW structure, that enables reconfiguration, consists on the AC/DC decoupling of this line thanks to two conductors, i.e. the Decoupled Empty Substrate Integrated Waveguide (DESIW). As can be seen in Figures 10 and 11, this structure is based on a grid of small squares in the bottom of the top cover, and each square has a polarization via to access from outside the structure when it is welded. In the top of this cover, a big square is milled to isolate the vias from the rest of the device. A line in X-band and a filter centered at 10.8 GHz have been designed and manufactured with this technology. The manufactured device and the frequency responses of the line and the filter are shown in Figures 10 and 11, respectively. The frequency response of the line presents low attenuation in transmission (S_{21}), and reflection (S_{11}) below 15 dB in the pass-band, thus making it adequate for applications with low requirements. The frequency response of the filter presents an important attenuation in the pass band, so further research in order to improve the electromagnetic results is required.

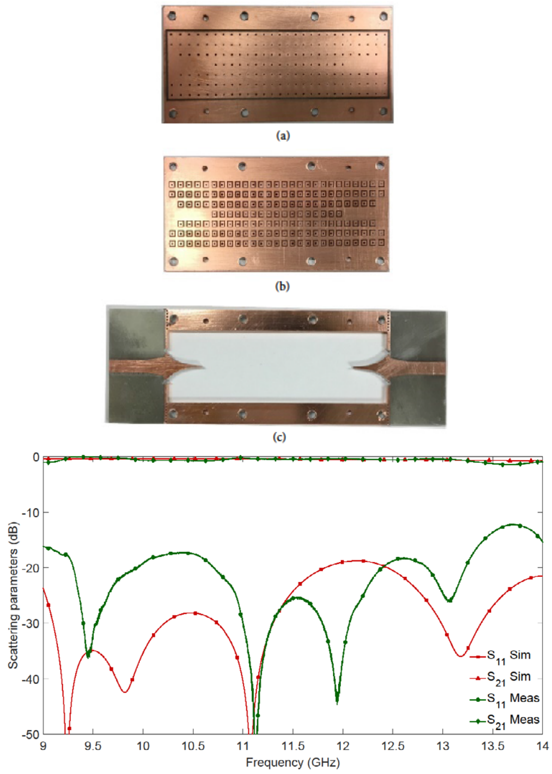

Figure 10. Decoupled Empty Substrate Integrated Waveguide (DESIW) line, detail of the different layers. Comparison of simulated and measured frequency responses.

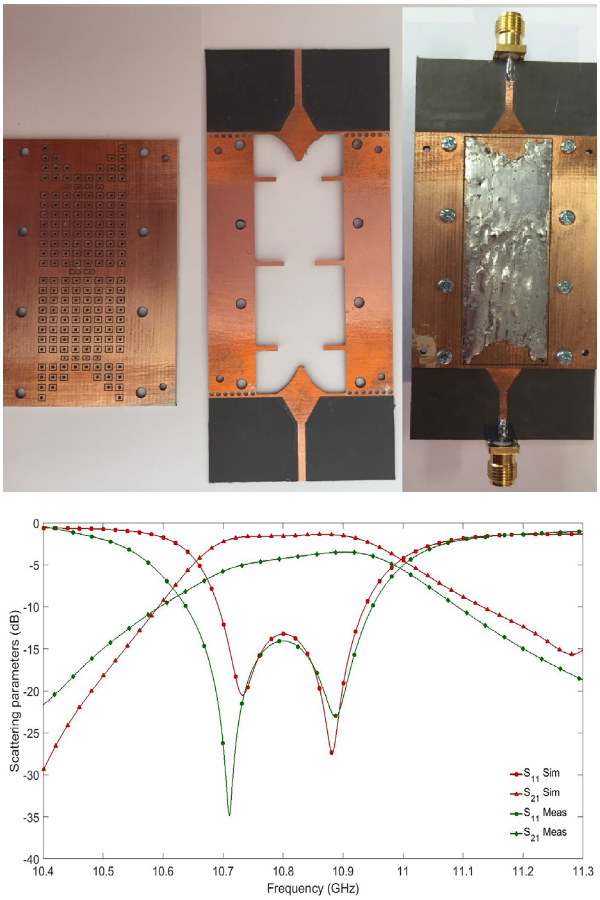

Figure 11. Decoupled Empty Substrate Integrated Waveguide (DESIW) filter, detail of the layers and assembled filter with connectors. Comparison of simulated and measured frequency responses.

The ESICL technology was used to design and manufacture a line, a power divider and a hybrid coupler. ESICL is a square coaxial line integrated in a bulk of metalized substrates, the structure has two conductors and the fundamental propagation mode is TEM.

Figure 12 shows the manufactured line and its frequency response. The transmission parameters are very close to the ideal ones (0 dB) and the reflection parameters are below -20 dB in the frequency range.

Figure 13 shows the direct hybrid coupler of 90° and Figure 14 its frequency response. In this realization the two branches divide the power equally (-3 dB in S_{31} and S_{41}), the input isolation is very high (S11 below -20 dB around the central frequency 5 GHz) as well as the isolation of the decoupled branch S_{21}.

Figure 15 presents the Y power divider and its frequency response in Figure 16. This realization divides the power equally between the two branches (-3 dB in S_{21} and S_{31}), and the input isolation is very high (S_{11} below -20 dB around the central frequency 5 GHz).

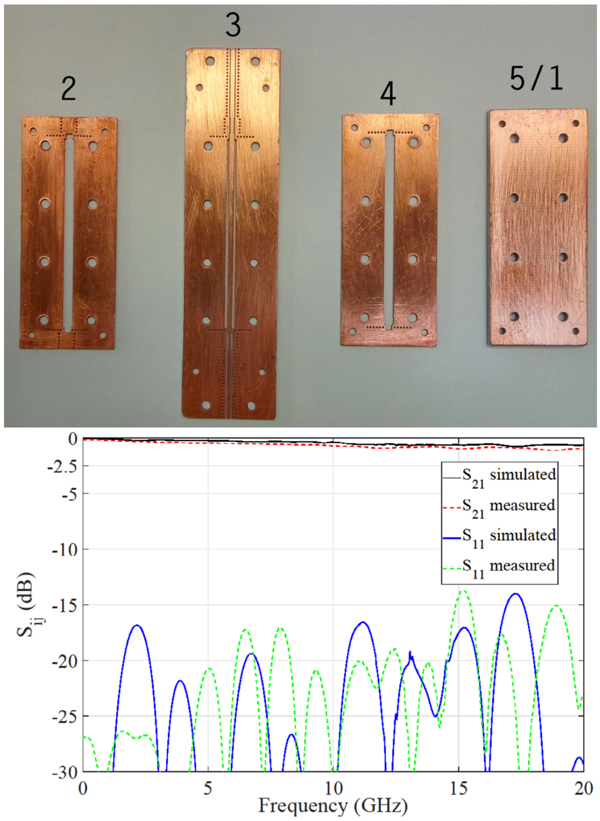

Figure 12. Empty Substrate Integrated Coaxial Line, detail of the different layers that compose the lines. Comparison of the simulated and measured frequency responses.

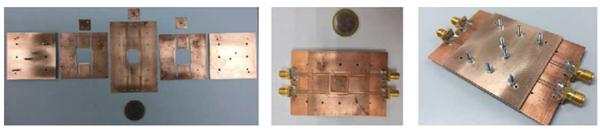

Figure 13. ESICL direct hybrid coupler of 90°, detail of the layers, the assembled prototype and the final result with connectors.

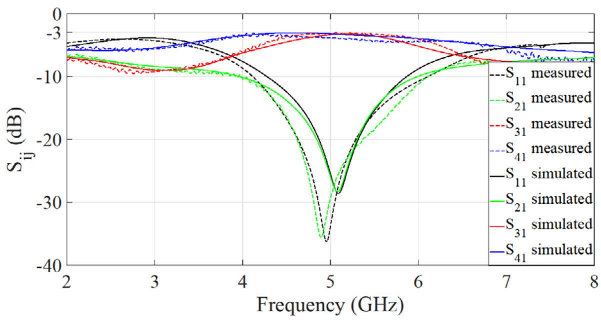

Figure 14. Comparison of simulated and measured frequency responses of direct hybrid coupler of 90°.

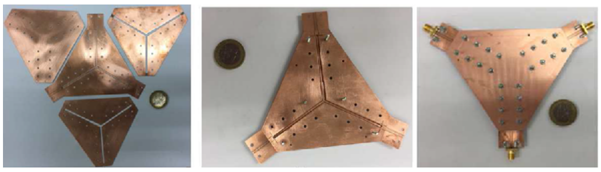

Figure 15. ESICL Y power divider, detail of the layers, the assembled prototype and the final result with connectors

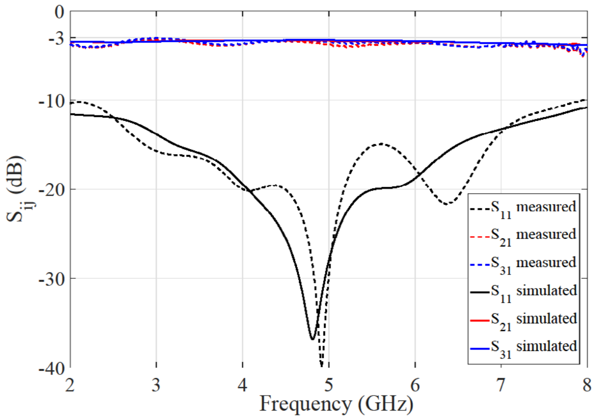

Figure 16. Comparison of simulated and measured frequency responses of the Y power divider.

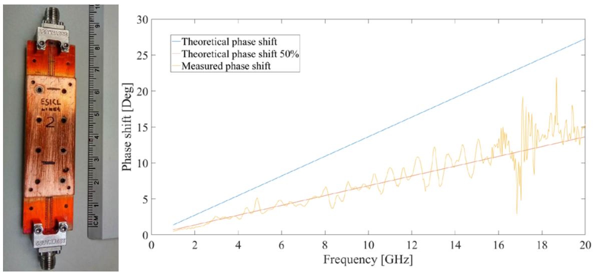

Figure 17: Phase shifter in ESICL technology. Comparison of theoretical and measured phase shift.

Finally, a phase shifter was designed and manufactured in ESICL technology as shown in Figure 17. To perform the phase shifter an ESICL line has been filled with liquid crystal, by applying a bias voltage to the active conductor of the coaxial line, the electric permittivity of the liquid crystal varies thus modifying the phase of the line response. The graph in Figure 17 shows the theoretical and measured differential phase between the two boundary polarization states. The insertion loss of the phase shifter is lower than 3 dB in the 1-20 GHz range, and the maximum phase shift is 21° at 17 GHz. These variables were obtained by applying a low frequency bias voltage of 200 Vpp at 1 kHz. Defining the Figure-of-Merit (FoM) as the maximum ratio of the phase shift and the insertion loss, the device performs a FoM of 8°/dB.

5.- CONCLUSIONS

In summary, it has been proven that passive microwave devices using novel hybrid SIC technologies are viable, easy to design and manufacture, and provide excellent performance. In addition, some strategies for the AC/DC decoupling of these lines have been developed to allow the introduction of reconfiguration elements. The electromagnetic performance of one of these elements with reconfiguration capability, the liquid crystal, has been studied in depth.

The results can be used in base stations of mobile communication systems, both in the input and output stages. The devices can also be used in feeding systems of arrays of beamforming antennas, in payload of satellites or in terrestrial equipment. All of them are, therefore, technical sectors with a great social and economic impact on our current and future Knowledge Society.

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7.- BIOGRAPHIES

Carmen Bachiller received her MSc degree in Telecommunication Engineering in 1996 and her PhD in Telecommunication in 2010 from the Universitat Politècnica de València. She worked from 1997 to 2001 in the ETRA I+D company as a project engineer in research and development on automatic traffic control, public transport management and public information systems using telecommunication technology. In 2001, she joined the Communication Department of the Universitat Politècnica de València as an assistant lecturer; she is an Associated Professor since 2011. She is teaching electromagnetism theory. She has participated in several teaching innovation projects and technological heritage studies. Her current research activities include modal methods for electromagnetic analysis, optimization and design of passive microwave structures, analysis and design of substrate integrated transmission lines and circuits and power effects in passive waveguide systems.

Juan R. Sánchez received his MSc degree in Telecommunication Engineering from the Universitat Politècnica de València in 2014 (with first-class honours). In 2015 he received an MSc degree, "Master Program in Electronics and Telecommunications" from Högskolan i Gävle, Sweden. In 2015 he gained a grant under the Fellowship Program for Training University Professors FPU14/00150 to get the PhD degree in Telecommunication, he is now working in the Microwave Application Group of the Institute of Telecommunications and Multimedia Applications of the Universitat Politècnica de València. His current research interests include analysis methods, computer aided design of passive microwave devices in waveguide, and substrate integrated waveguide technologies.

Vicente Nova received his MSc degree in Telecommunication Engineering from the Universitat Politècnica de València in 2016. He made his master's degree project on ESICL broadband transitions. His current research includes optimization and design of substrate integrated microwave devices, design and manufacture of SICs lines and design of reconfigurable devices using anisotropic materials.

José M. Merello received his BSc degree in Telecommunication Eengineering from the Universitat Politècnica de València in 2017. He made his final degree project on analysis and design of passive devices on ESICL. Currently, he is studying in order to get an MSc degree in Telecommunication Engineering.

Vicente E. Boria was born in Valencia, Spain, on May 18, 1970. He received his Ingeniero de Telecomunicación degree (with first-class honours) and the Doctor Ingeniero de Telecomunicación degree from the Universidad Politècnica de València, Valencia, Spain, in 1993 and 1997, respectively. In 1993, he joined the Departamento de Comunicaciones, Universidad Politècnica de València, where he has been Full Professor since 2003. In 1995 and 1996, he was holding a Spanish Trainee position with the European Space Research and Technology Centre, European Space Agency (ESTEC-ESA), Noordwijk, The Netherlands, where he was involved in the area of EM analysis and design of passive waveguide devices. He has authored or co-authored 10 chapters in technical textbooks, 160 papers in refereed international technical journals, and over 200 papers in international conference proceedings. His current research interests are focused on the analysis and automated design of passive components, left-handed and periodic structures, as well as on the simulation and measurement of high power effects in passive waveguide systems. Dr. Boria has been a member of the IEEE Microwave Theory and Techniques Society (IEEE MTT-S) and the IEEE Antennas and Propagation Society (IEEE AP-S) since 1992. He is member of the Editorial Boards of the IEEE Transactions on Microwave Theory and Techniques, IEEE Microwave and Wireless Components Letters, Proceeding of the IET (Microwaves, Antennas and Propagation), IET Electronics Letters and Radio Science. Presently, he serves as Associate Editor of IEEE Microwave and Wireless Components Letters and IET Electronics Letters. He is also a member of the Technical Committees of the IEEE-MTT International Microwave Symposium and of the European Microwave Conference.