Multi-band RF and mm-Wave Design Solutions for Integrated RF Functions in Liquid Crystal Polymer System-On-Package Technology

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Abstract

Electronic packaging evolution involves systems, technology and material considerations. In this paper, we present a liquid crystal polymer (LCP) based multilayer packaging technology that is rapidly emerging as an ideal platform for low cost, multi-band and reconfigurable RF front-end module integration. LCP's very low water absorption (0.04%), low cost and high electrical performance makes it very appealing for RF applications. Here we describe main characteristics and real performance of LCP substrate, by means of several design examples. A Single-Input-Single-Output (SISO) dual-band filter operating at ISM 2.4-2.5 GHz and UNII 5.15-5.85 GHz frequency bands, a dual polarization, dual frequency 2x1 antenna operating at 14 and 35 GHz, and a WLAN IEEE 802.11a compliant compact module (volume of 75x35x0.2 mm^3) have been fabricated on LCP substrate, showing the great potential of the System-On-Package approach for 3D compact, multi-band and reconfigurable integrated RF and millimeter waves functions and modules.

Introduction

Miniaturization, portability, cost and performance have been the driving force for the evolution of packaging and system-on-package (SOP) approach in RF, microwave and millimeter wave applications. Recent research shows SOP to be a more feasible and low cost solution than system-on-chip (SOC) approach [1]. Cost, electrical performance, integration density, and packaging compatibility are variables that are often at odds with each other in RF designs. Few material technologies are able address these considerations simultaneously. LTCC is a technology that has excellent electrical performance, dense multilayer integration, and good barrier properties, but it is relatively expensive compared to standard FR4. Most other substrate and packaging materials do not have low enough water absorption properties in tandem with multilayer construction capabilities to be considered for vertically integrated designs. Liquid crystal polymer (LCP) provides the all-in-one solution for such integration approach in terms of high quality dielectric for high performance multiband passive design, excellent substrate for heterogeneous SOP integration as well as for MEMS structures, enabling the implementation of multiband and reconfigurable modules.

In this paper, we present the potential of LCP as the substrate as well as the packaging material for wireless applications. In the following sections, the LCP fabrication process, its main characteristics and design examples will be described. A Single-Input-Single-Output (SISO) WLAN dual-band filter using the novel "dual behaviour resonators" technique will be shown. Exploiting the strong second resonant frequency of resonators to realize the filtering response, allows for achieving the asymmetric shape and the good rejection between the two bands. A good agreement between simulation and measurements results will be reported.

A dual polarization, dual frequency 2x1 antenna array on LCP will also be presented. The frequencies of operation are 14 and 35 GHz. The 14 GHz antenna array is placed on the top layer of the LCP substrate, while the 35 GHz antennas are "sandwiched" in between the 14 GHz array and the ground plane on an embedded layer. Both arrays are fed by microstrip lines printed on the same layer as the corresponding array. The control of polarizations can be realized by the use of two small gaps in the feed lines, which introduces a small capacitance in each gap. Each array has been simulated and measured, separately, showing good agrrement. This design exhibits a high efficiency and a low cross-polarization level.

Finally an example of WLAN IEEE 802.11a compliant module on LCP will be also shown to demonstrate the power of this technology. A wireless transceiver system has been implemented, exploiting the capability of LCP to enable for low loss interconnections as well as for integration of embedded passives. It includes up-converting and down-converting stages, image canceling BPFs, PA module and variable gain LNA on the receiver side. The system has been measured and experimental results will be reported to show the great potential of the LCP as a valid altrnative for MCM and SOP approaches.

LCP Process and Integration Concept

Multi-layer substrates have been and still are of great interest for research in the area of the 3D integration of RF and millimeter waves functions and module using the System-on-Package (SOP) approach.

Our research has been focused mainly on advanced multi-layer organic substrates using FR4 material and advanced material such as liquid crystal polymer (LCP), as well as on ceramic based platform such as Low Temperature Co-fired Ceramic (LTCC). The choice of the most suitable technology depends on the application specifications such as environment, frequency of operation, performances, volume and cost. Multi Layer Organic substrates are now widely developed and used in the High Density Interconnect (HDI) industry. They used very low cost substrate such as FR4 and low cost advanced epoxy and polyimide as dielectrics, and tend to dominate the market for high volume applications up to GHz frequency range. LTCC has been widely used for RF and millimeter waves applications because of its process maturity and stability and its relatively low cost. Multi-layer capability up to 20 metal layer makes LTCC very attractive for 3D integrated embedded components such as filter and antenna in a very compact and cost effective manner [1].

Liquid Crystal Polymer (LCP) is proving to be a valid alternative for high frequency designs due to its ability to act as both the substrate and package for multilayer constructions. It is a fairly new, low cost thermoplastic material [2] and its unique performance for an organic material is comparable to ceramic-based substrates that are widely used in RF and microwave applications (see Table I). Its dielectric constant is 2.9 at 20 GHz and increases very slightly with frequency up to 110 GHz, while the loss tangent is very small (~0.002). The low coefficient of thermal expansion (CTE) ($8\text{-}17 \cdot 10^{-6}$) leads to better matching to silicon or chip package and provides better reliability. The low moisture absorption (~0.04%) enables a better stability of performances. LCP offers large area processing capability that leads to tremendous cost reduction compared to commonly used LTCC substrate. Using vertical space allows the passive elements in RF front-ends to be efficiently integrated. However, processing challenges such as LCP-metal adhesion and bond registration have delayed widespread LCP implementation. Metal adhesion has recently been solved, and bond optimization is under active pursuit. Once the process is commercially available, LCP will be situated as a prime technology for enabling system-on-package RF designs.

TABLE I

COMPARISON OF SUBSTRATE PROPERTIES

	FR4	LTCC	LCP
Dielectric constant	4.5@1MHz	5.6@20GHz	2.9@20GHz
Loss Tangent	0.02	0.0012	0.002
CTE	$15\text{-}20 \cdot 10^{-6}$/K	$5.9 \cdot 10^{-6}$/K	$8\text{-}17 \cdot 10^{-6}$/K
Cost	Very Low	Low/Medium	Low

The loss characterization of LCP transmission lines up to W band provides an excellent insight of its potential for mm-wave applications. Conductor backed CPW (CB-CPW) transmission lines have been fabricated on 50μm thick LCP substrates with measured insertion loss of 2.24 dB/cm at 110 GHz [3].

LCP has also been proven to be an excellent material to design high Q spiral inductors. The measured results exhibit very good quality factors as high as 90 from C to X-band, for inductance values ranging from 2 to 5 nH [4-6]. The low cost, low loss and easy integrability of LCP has already been addressed in [1].

Material, electrical and economical considerations make LCP a serious candidate for all Multi-Chip-Module (MCM), Systems-On-Package (SOP) and advanced packaging technology lead by the tremendous growing market for Digital, RF and Opto-RF applications. But the fabrication of SISO dual band filters and MEMS switches extend the platform to multiband and reconfigurable applications.

Figure 1 illustrates the proposed module concept. Two stacked SOP multi-layer substrates are used and board-to-board vertical transition is insured by μBGA balls. Standard alignment equipment is used to stack the board and thus provide a compact, high performance and low cost assembly process. Multi-stepped cavities into the SOP boards provide spacing for embedded RF active devices (RF switch, RF receiver and RF transmitter) chipset and thus lead to significant volume reduction by minimizing the gap between the boards. Active devices can be flip-chiped as well as wire-bonded. Cavities provide also integration opportunity for MEMSs devices such as MEMS Switch. Passive components, off-chip matching networks, embedded filter and antenna are implemented directly into the SOP boards by using multi-layer technology [7-11]. Standard BGA balls insure interconnection of this high density module with a mother board such as FR4 board. The top and the bottom substrates are dedicated respectively to the receiver and transmitter building blocks of the RF front-end module. Figure 2 shows the RF block diagram of each board.

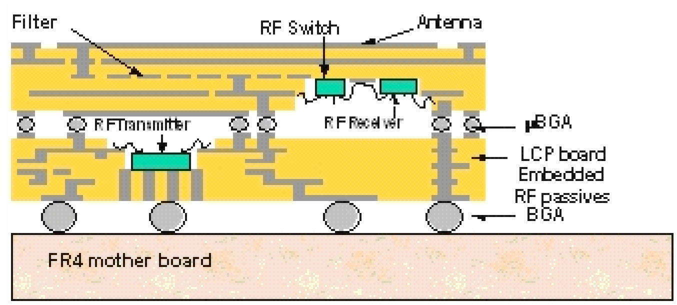

Fig.1. 3D integrated module concept view.

The receiver board includes antenna, band-pass filter, active Switch, RF receiver chipset (LNA, VCO and Down-conversion Mixer). The Transmitter board includes RF Transmitter chipset (Up-converter Mixer and power amplifier) and off-chip matching networks. Ground planes and vertical via walls are used to address isolation issues between the transmitter and the receiver functional blocks. Arrays of vertical vias are added into the transmitter board to achieve better thermal management.

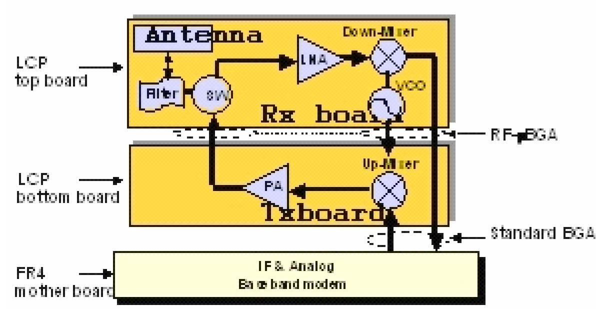

Fig.2. RX and TX board block diagram.

Single-Input Single-Output (SISO) WLAN LCP Dual-Band filter

A Single-Input-Single-Output (SISO) LCP dual-band filter has been synthesize basing on the novel "dual behaviour resonator" technique [12]. The WLAN operating frequency bands, ISM 2.4 GHz and UNII 5 GHz, have been targeted because of the ever growing number of services allocated in this part of the spectrum, including Bluetooth, IEEE 802.11a/b/g, and the introduction of dual-band wireless systems. WLAN Dual Band systems allow, in fact, the WLAN users the freedom of using their preferred frequency whenever they need it, operating on the recent 802.11a 5 GHz for high speed resolution or the popular 802.11b/g 2.4 GHZ for mass access. Most of the products that can be found in the market offers a dual path architecture. The goal is to exploit the same RF path (SISO), providing support to multi-standards and multi-bands on a single platform, while maintaining performances and compactness.

The dual behaviour resonators (DBRs) technique is based on the parallel association of two open-ended stub resonators. The open-ended stub is, in fact, the simplest realization of a band-stop structure and shows a dual behaviour in the band-pass and stop-band regions: using the open stub means inserting a transmission zero, whose resonance frequency can be easily controlled by adjusting the stub length, and plus by playing with the several degrees of freedom that a microwave design offers. If the stubs are properly connected under constructive recombination criteria, the result is a band-pass response created between the lower and the upper rejected bands. The same approach has been extended to obtain a dual-band narrow band pass filter, simply adding a third resonator to create a third transmission zero. The procedure described in [13] has been applied to the design of the present filter in order to have first guess values for lengths and characteristic impedances (widths). In this case, the location of the transmission zeros has been accurately chosen in order to control the width and the location of the desired bands, successfully exploiting the second resonance frequency. The desired bands, 2.4-2.5 GHz and 5.15-5.85 GHz, are, in fact, very different in terms of width (narrow band at 2.4 GHz, wide band at 5 GHz). Moreover the channel spacing is wide and a good rejection is difficult to achieve with the standard technique. On this basis, the stubs have been dimensioned in order to have transmission zeros at 2.2 GHz, 2.93 GHz and 3.14 GHz.

The design procedure followed the steps described in figure 3. To realize the pass-band in the 5 GHz range, the second resonance frequency of the first stub has been successfully exploited, while the close transmission zeros at 2.9 and 3.14 GHz allows a better rejection in the inner stop band. To achieve better selectivity the second order filter, shown in figure 4, has been considered. The folded design has been inspired to avoid the impact of stub excessive length on the overall filter size.

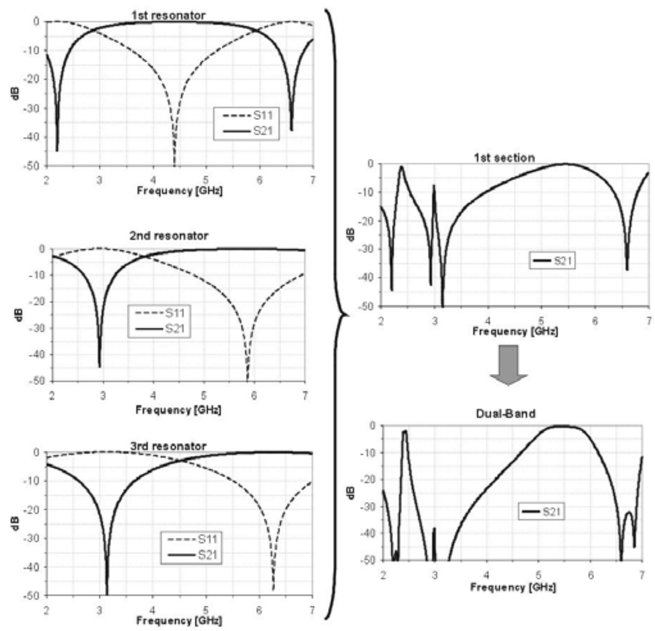

Fig.3. WLAN Dual-Band filter design procedure.

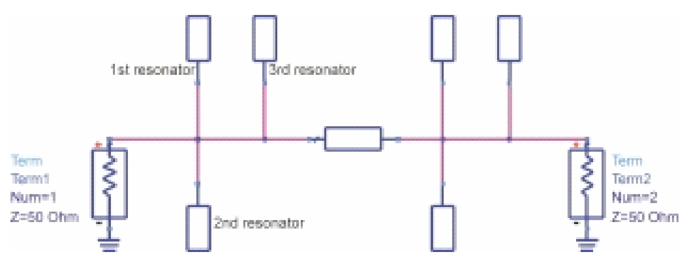

Fig.4. Filter schematic.

The prototype, shown in figure 5, has been fabricated in LCP substrate, characterized by ε_r 2.9, tanδ 0.002, substrate thickness 275 μm, conductor thickness 9 μm. Figure 6 shows the good agreement between simulation versus measurement. The insertion loss and return loss at the central frequency are 2.4dB and 15dB for the 2.4 GHz band, respectively, and 1.8dB and 10dB for the 5 GHz band, respectively. It exhibits also an out-of-band rejection as high as 45 dB between the L and C band.

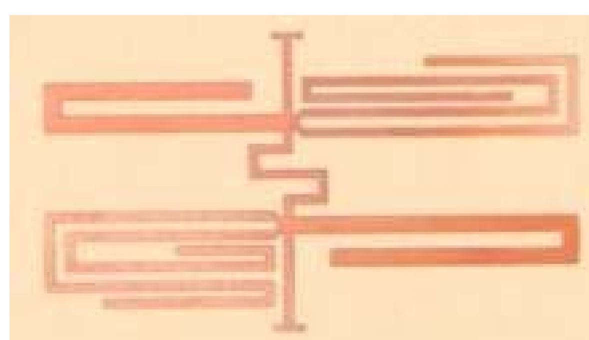

Fig.5. Photograph of the fabricated Single-Input-Single-Output (SISO) LCP dual-band filter

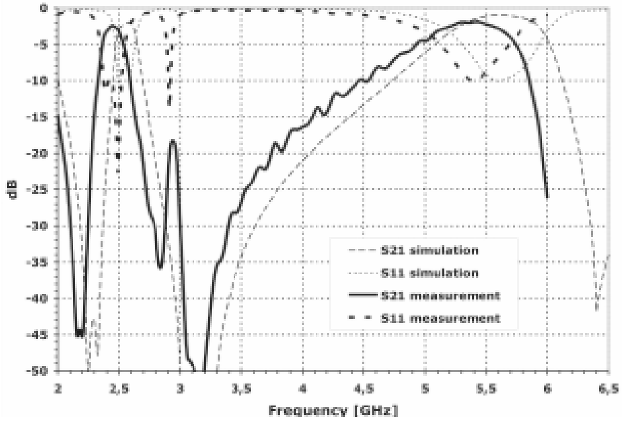

Fig.6. Measurement compared with simulated performances of the SISO LCP dual-band filter

Dual Frequency/Dual Polarization microstrip antenna arrays on LCP

Two dual polarization, dual frequency 2x1 antenna arrays on LCP multilayer laminated substrates have been designed at operating frequencies of 14 and 35 GHz. The top view of the fabricated 2x1 antenna arrays is shown in Fig. 7. The metal is copper (Cu) and has a thickness of 18 µm. The total substrate thickness for the design is 425 µm, consisting of two LCP layers (each 200 µm thick) and a 25 µm bonding layer. Such value has been chosen in order to achieve at least a 1.5% impedance bandwidth at -10 dB, while maintaining a compact structure. The 14 GHz antenna array is placed on the top layer of the LCP substrate (at the interface of LCP and air), while the 35 GHz antenna array is "sandwiched" between two embedded layers for compactness and crosstalk minimization reasons. The LCP layer under the 35 GHz antenna array has a thickness of 200 µm. Both arrays are fed by microstrip lines printed on the same layer as the corresponding array. To further prevent parasitic coupling between the two antenna arrays, the antennas in the 35 GHz array have a linear (diamond) configuration. The control of polarizations is realized by means of two small gaps in the feedlines for two perpendicular directions, which introduce a small capacitance in each gap. The small capacitance on the order of fF's in the gap represents high impedance or a "near" electrical open circuit which prevents the mode excitation of the corresponding polarization. RF MEMS switches or pin diodes can be utilized to achieve this effect by turning on in order to excite a specific polarization and turning off in order to switch to the alternative polarization.

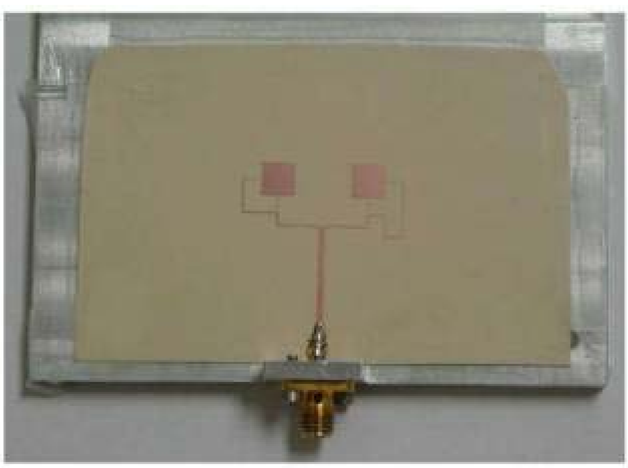

Fig.7. Top view of the fabricated 2x1 array antenna

Simulations of both arrays were performed, separately, using the 3D full-wave simulation programs, EmPicasso and Micro-Stripes. Plots of the simulated and measured results for the return loss versus frequency of both polarizations at each frequency are shown in Fig. 8.

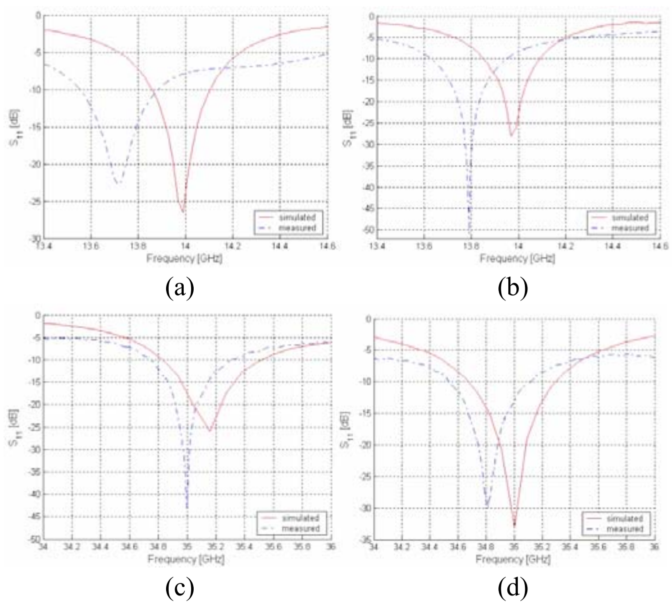

Fig.8. Simulation and measurement results for the return loss versus frequency of the 2x1 array for: a) 14 GHz array, pol.X, b) 14 GHz array, pol.Y, c) 35 GHz array, pol.X, d)) 35 GHz array, pol.Y.

The simulated results show a return loss of approximately -26 dB at a center frequency (f_c) of 13.99 GHz for polarizations X (x-directed feed) and -27 dB at f_c=13.97 GHz for polarization Y (y-directed feed) for the 14 GHz structure. Additionally, the 35 GHz structure exhibits at return loss of approximately -25 dB at f_c=35.15 GHz for polarization X and -32 dB at f_c=35 GHz for polarization Y. The measured results for the return loss are as follows: the 14 GHz array has a return loss of approximately -23 dB at f_c=13.72 GHz and -51 dB at f_c=13.79 GHz for polarizations X and Y, respectively, while the 35 GHz array has a return loss of approximately -44 dB at f_c=35 GHz and -30 dB at f_c=34.81 GHz for polarizations X and Y, respectively. It can be seen that a good agreement is observed between the simulated and measured results for the return loss versus frequency plots for the 2x1 sub-array. The -10 dB return loss percent bandwidths for the measured results are approximately as follows: 2.41% and 2.47% for polarizations X and Y, respectively, for the 14 GHz array and 1.57% and 1.72% for polarizations X and Y, respectively, for the 35 GHz array. The simulated results produced an efficiency of better than 85% for all array antenna designs.

The variation in the simulated and measured results of the return loss for the 14 GHz polarization Y array and the 35 GHz polarization X array can possibly be attributed to a decrease in frequency points used in the simulations. The use of more time steps may show a lower return loss for the simulated plots. A finer discretizaton of cells in the simulations can also possibly lead to a lower return loss values but at the expense of increased computational time. The difference in return loss for the measured results both polarizations at 14 GHz and 35 GHz can be attributed to fabrication tolerances. The slight increase in impedance bandwidth for the measured results in comparison to simulations is a result of the substrate thickness in fabrication being about 7 µm greater than that used in the simulations. The frequency shifts in the measured results can also be attributed to fabrication tolerances. Such frequency shift has been measured for both polarizations of the 35 GHz design and may be the cause of the difference in percent bandwidth, while in the 14 GHz designs, measurements inaccuracies are the probable cause of the difference in percent bandwidths.

WLAN Module Implementation

A functional RF compact module (volume of 75x35x0.2 mm^3) compliant with the IEEE 802.11a WLAN applications, incorporating LCP board technology, has been designed and measured (Fig.9). The architecture is a superheterodyne Tx/Rx system. Two passive mixers, achieving higher linearity, up-convert the low IF (20 MHz) OFDM signal to the 5.x GHz frequency band (Fig.10) and two BPF operations cancel the unwanted images after each mixing.

Driver stages provide the gain needed to balance out the losses due to passives, while the PA module demonstrating a P_{1dB} of 30 dBm enables for operation at a back-off of 6 dB,

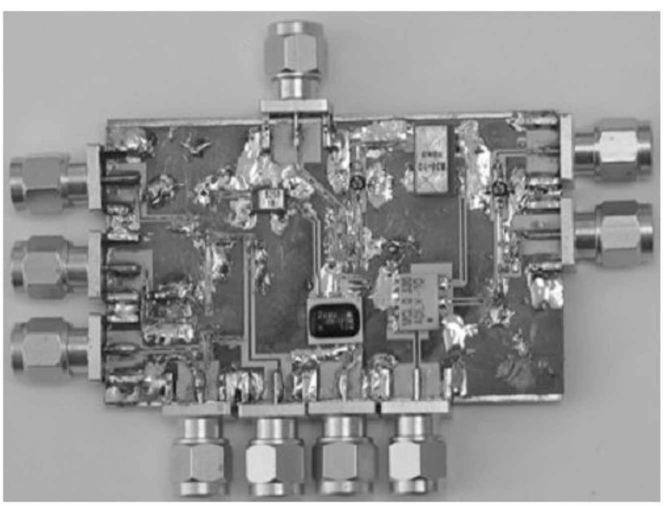

Fig. 9. Photo of WLAN module

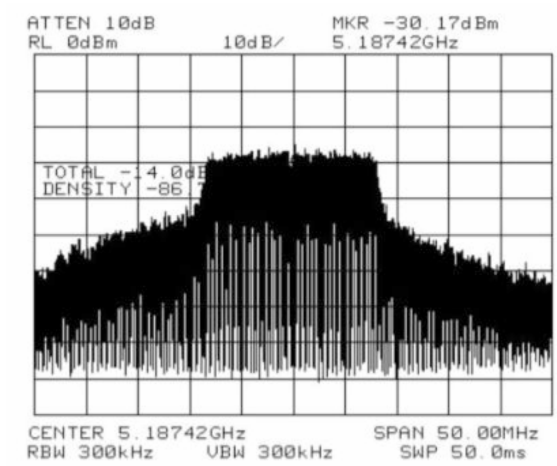

Fig.10. OFDM signal with carrier frequency = 5.18 GHz and channel power = -14 dBm

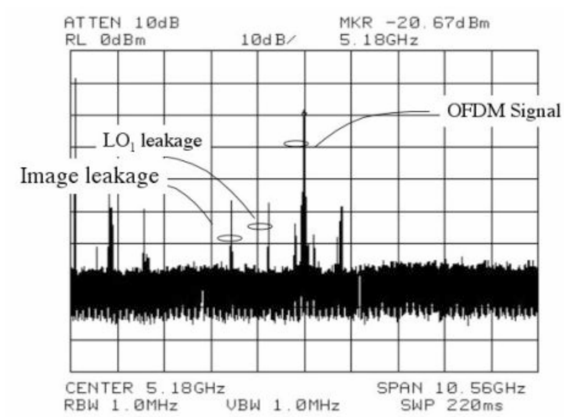

Fig.11. Image and LO_1 cancellation in the receiver

which is a prerequisite for OFDM transmission. The receiver exploits a variable-gain LNA for linearity considerations. Inspection of frequency spectrum of the signal at the output of the Tx module (Fig. 11) shows that the leakage of the local oscillator signal is efficiently suppressed to 48 dBm as well as the leakage of the unwanted image at LO2-LO1. The receivers
overall NF is lower than 8 dB in order to enable for proper RF reception and then demodulation of signals as low as –70 dBm.

Conclusions

We have demonstrated the potential of LCP as the platform for multiband, reconfigurable integrated RF and mm-wave modules. A SISO dual band filter with excellent loss performance for WLAN applications in L and C band (2.4 dB in L band and 1.8 dB in C band respectively) has been reported. A dual polarization, dual frequency 2x1 antenna array on LCP operating at 14 GHz and 35 GHZ with high efficiency as high as 85% and a low level of cross-polarization, has been designed and measured. Finally, a WLAN IEEE 802.11a compliant compact module (volume of 75x35x0.2 mm^3) have been fabricated on LCP substrate.The receiver shows a high sensitivity (~ -70 dBm), low noise figure (<8 dB) and high LO leakage suppression of 55 dB. The transmitter works at a 6 dB back off from output P_{1dB} of 30 dBm.

As a conclusion, LCP constitutes an all-in-one solution for the heterogeneous SOP 3D integration for multiband and reconfigurable RF and mm-wave applications.

Acknowledgments

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