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On the Design of Laser Structured Ka Band Multi-Chip Module

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Abstract

The rapid prototyping of millimeter wave (MMW) multi-chip module (MCM) on low-cost ceramic-polymer composite substrate using laser ablation process is presented. A Ka band MCM front-end receiver is designed, fabricated and tested. The complete front-end receiver module except the IF and power distribution sections is realized on the single prescribed substrate. The measured receiver gain, noise figure and image rejection is 37dB, 4.25dB and 40dB respectively. However, it deduced from the experimental results of the two front-end modules that the complex permittivity characteristics of the substrate are altered after the laser ablation process. The effective permittivity alteration phenomenon is further validated through the characterization and comparison of various laser ablated and chemically etched Ka band parallel-coupled band-pass filters. A simple and experimentally verified method is worked out to utilize the laser ablation structuring process on the prescribed substrate. It is anticipated that the proposed method can be applied to other laminated substrates as well with the prescribed manufacturing process.

Keywords: *multi-chip module, millimeter wave, laser ablation, permittivity, band-pass filter*

1. Introduction

In the recent years, MMW imaging technology has gained significant benefit from the rapid development of microwave monolithic integrated circuit (MMIC) and multi-chip module (MCM) technology. One of the design approaches is to realize the whole MMW radio system on a single chip. With the advancement in the device technology, such contemporary MMW systems are mature and have evolved from laboratory prototypes into robust commercial products. This design approach offers some very attractive advantages when compared with the other design options. One of the primary advantages is the reduced mass and volume when compared with the conventional circuit assemblies. Besides these, such systems realized on a single MMIC exhibit highly repeatable performance and offer low-cost solution for mass production [1, 2]. However, the disadvantage associated with this approach restricts its utilization at large scale. Firstly, the realization of MMW systems on a single MMIC requires design proficiency and expertise. The time cycle from chip design to chip tape-out typically clocks around one year. Moreover, usually the design has to undergo through multiple iterations before acceptable performance is achieved. This consumes elevated resources in terms of time and cost. This results in log-time-to-market solutions which is obviously not a preferred choice for commercial products. Further, passive structures realized on a MMIC chip typically have low quality (Q) factor. Consequently, such passive structures are often realized off-chip.

Instead, the MMW radio systems are realized at multi-chip module (MCM) level [3, 4]. The design of MMW receivers usually comprises of interface transitions. Such transitions dominate the system performance in terms of bandwidth, system losses, noise and size. The bond wire interconnects between the MMIC and printed circuit adds discontinuity. This results in mismatch due to the parasitic inductance and introduces additional signal loss. The shielding enclosure tolerances have pronounced effects on the performance of MCM at MMW frequencies. Higher order mode propagation inside the enclosure may adversely degrade the circuit performance while the planar passive structure such as filters, couplers are sensitive to the side wall and top plate distances. One of the important dimensions of MMW multi-chip module design is the manufacturing tolerances. This includes both the printed circuit as well as

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the mechanical tolerances [5]. Nevertheless, when compared with MMIC system-on-chip approach, the MCM level design approach is more viable due to the lesser design complexity and shorter prototyping time cycle. In this work, the MCM level design approach is adopted for realization of the proposed low-cost, compact front-end receiver. The rest of the paper is organized as follows. Section II describes the different manufacturing options for MMW printed circuits. Their merits and demerits are discussed. The design and measured results of two Ka band front-end receivers are presented in section III. Further, section III describes the characterization of laser ablated and chemically etched Ka band parallel-coupled band-pass filter (BPF). A simple, experimentally verified method is proposed in section IV to utilize the laser ablation structuring process on the prescribed substrate. Section V contains the conclusion.

2. Printed Circuit Manufacturing

The design of millimeter wave (MMW) systems is an iterative process. The design cycle of a conventional photolithography process contains tedious steps which have to be followed for each iteration. This consumes additional resources, mainly in terms of time and cost. The photolithography process aided with the chemical etching often does not provide enough geometric precision necessary for MMW planar structures. The post manufacturing analysis shows that a reduction occurs in the length and width of the trace. Such reduction is not very well controlled and repeatable; rather it depends on the process conditions. MMW planar structures are sensitive to such inaccuracies and most often such inaccuracies are not acceptable. Further, the microscopic examination of post-etched printed circuits show that the right-angled corners convert to round ended shapes. At MMW frequencies, the effect of this occurrence is more pronounced especially in resonant structures. Another problem with the conventional process is the reproducibility. The statistical data obtained from the measurement of a large number of samples indicates a high standard deviation error. Further, the minimum realizable trace width and gap between the two traces is 100µm. This limitation restricts the design of MMW passive structures with optimum performance as well [6]. Besides these, different kinds of defects have been experienced during manufacturing such as un-etched gaps, trace breakage etc. Figure 1 shows a Ka band parallel-coupled BPF manufactured with conventional process. Figure 1(a) shows a 100µm wide gap of a coupled-line resonator which remained un-etched during the fabrication. Figure 1(b) shows a broken trace. Last but not the least, the chemicals used in the etching process is harmful to human and environment safety. In order to address the issues associated with the conventional process, and alternative is to adopt the thin film technology. MMW circuits realized on ceramic substrates with thin film technology exhibits good accuracy and reproducibility, however, at much higher cost.

Unlike conventional photolithography printed circuits manufacturing, laser structuring offers the fastest, highly repeatable and most accurate manufacturing solution. Lately, with the advent of the modern laser ablation process with ultraviolet (UV) and infrared (IR) laser machines, the fabrication of MMW printed circuits is possible with the highest speed, accuracy and reproducibility [7]. This kind of printed circuit manufacturing is well suited for MMW circuit design as multiple iterations are required to obtain desired specifications. The removal of the copper metal layer from the top surface of the substrate is done with the interaction of laser light with copper. The ideal wavelength of a laser source is where the copper exhibits a high degree of energy absorption. At such wavelengths, the relative degree of absorption of copper initiates the ablation process. In the rapid prototyping of MMW planar circuits with laser ablation process, first the contours of the conductive path structure are produced. Later, the remaining copper surfaces are removed [8]. It may be noted that the manufacturing tolerances of the thin film and the laser structuring technologies are comparable while the inaccuracy of the conventional process could be even larger than ± 25µm if the process is not well controlled. The fabrication technique based on femtosecond laser ablation process is being extensively used for digital, analog and low frequency radio circuits. However, the literature survey reveals that the implications of laser ablation process on MMW circuits realized on thin-core composite materials is not yet potentially explored. Few microwave and MMW components fabricated with laser ablation process are reported. In [8], the design of a log periodic antenna fabricated on RT5870 substrate using laser ablation process is discussed. The antenna operates from 1GHz to 5.8GHz. In [9], the design of a Ka band frequency trippler module realized on low cost, high frequency laminate (Arlon AD1000) using laser ablation process is discussed.

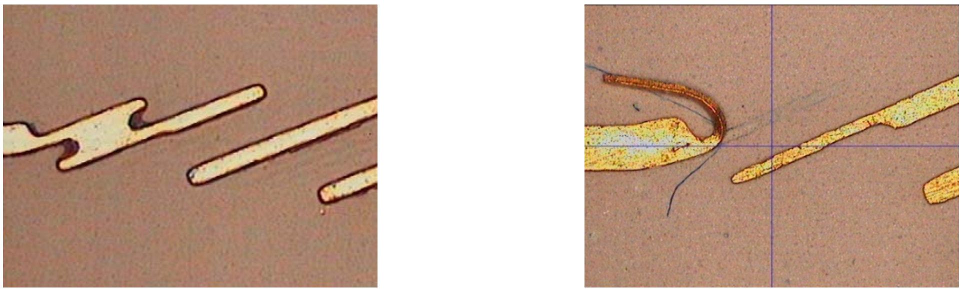

(a) (b)

Figure 1. Conventional Process Defects (a) un-etched, (b) damaged trace

3. Multi-Chip Module Design

Over the years, various Ka band front-end receivers have been reported [10, 11]. In [10], a substrate integrated waveguide (SIW) filter is employed in the front-end receiver for image rejection. A SIW filter occupies relatively much larger space than the microstrip parallel-coupled filters. Thus, such planar waveguide structures are not suitable for applications where space is limited. The front-end module in [11] utilizes an active in-phase/quadrature-phase (I/Q) mixer and a 90° hybrid divider to perform image frequency rejection. Image suppression of 15 dB is achieved with this configuration. Such configuration also occupies a large space and the active IQ mixer consumes additional power as well. The achieved image rejection is relatively much lower than the typical desired value of 25dB. In this work, we have adopted single-stage super-heterodyne configuration for the front-end receiver realization. The single-stage down conversion reduces the requirement of hardware resources and the complexity of the whole design. Conversely, the design of the image rejection filter becomes more vital as the image lies close to the MMW frequency due to the low intermediate frequency (IF). The specifications of the Ka band MCM receiver are tabulated in Table 1. The design scheme of the MCM is mainly dictated by the available volume which is restricted to 120x20x20 mm^3. Ceramic substrates such as alumina being expensive are not considered. Such substrates with the thin film technology process further results in higher cost. Moreover, at MMW frequencies, high relative dielectric constant (E_r) such as 10 put stringent requirements on machining tolerances. Consequently, the realization of some of the distributed structures with extremely narrow dimensions may become impractical due to the manufacturing limits. A low-cost commercially available ceramic filled Teflon substrate (E_r=6.2, 0.254mm thickness) is chosen for this work. In order to realize the front-end in the given volume, die chips are preferred over an SMT package. Further, the compact size of the die chip allows ease of fabrication for a narrow channel cavity with cutoff frequencies higher than the operating frequency.

Table 1. MCM Specifications

Parameter	Specifications
Operating frequency	33~35 GHz
LO frequency	32 GHz
IF frequency	2 GHz
Gain	40 dB
Image rejection	>30 dB
Noise figure	4 dB

The front-end receiver block diagram is depicted in Figure 2. For compact realization, a two-layer planar technology is adopted. These two layers have been labeled as a top layer and the bottom layer. The top layer comprises of active devices and passive structures such as filters, matching networks. The complete top layer components operating from 2GHz to 34GHz are realized on a single piece of substrate using laser ablation process. This facilitates ease of manufacturability and seamless integration. The blocks enclosed in the solid line box in Figure 2 illustrate the top layer. The bottom layer comprises of chip low pass filter (LPF), IF amplifier and step-impedance microstrip BPF. The blocks enclosed in the dotted outline depict the bottom layer as shown in Figure 2. Figure 3(a) and (b) illustrates the top and bottom sections of the front-end receiver prototype respectively with reference to the block diagram shown in Figure 2.

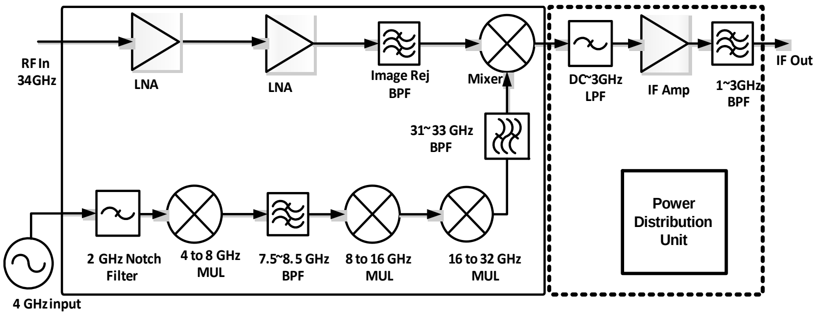
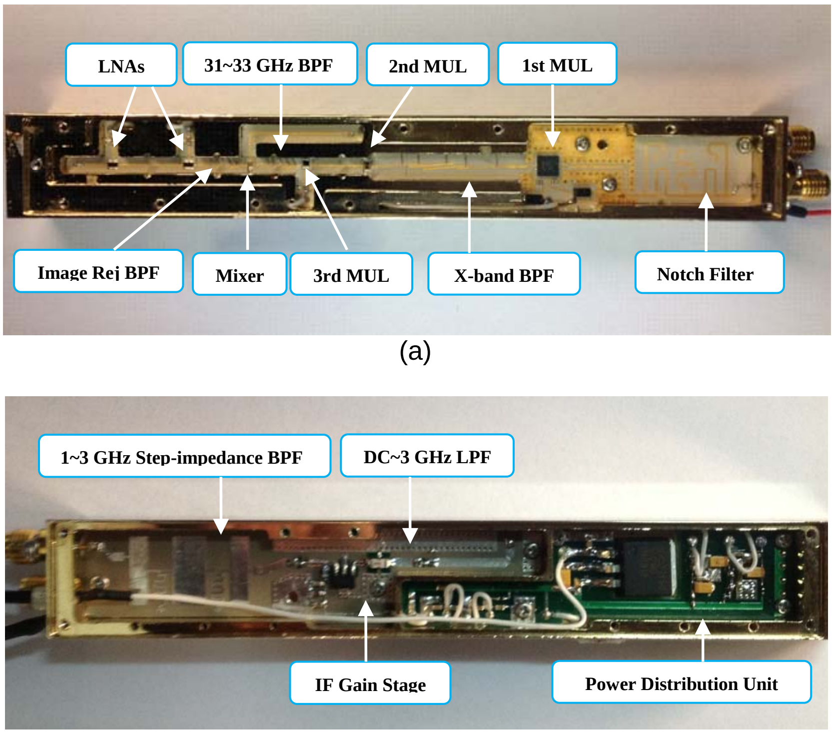


Figure 2. Functional Block Diagram of MCM Receiver



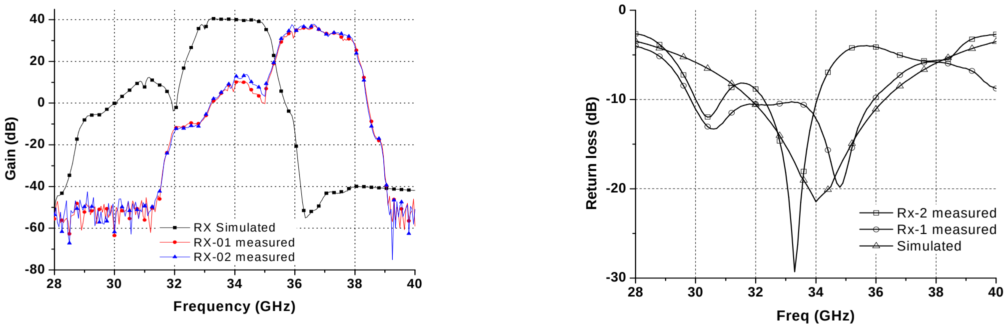
(a)

(b)

Figure 3. Ka band Front-end Receiver (a) Top section (b) Bottom section

A reactively tuned waveguide-to-microstrip transition is employed in this work because of its simplicity and ease of integration. The other advantage is that the front-end receiver with such kind of transitions can be hermetically sealed later for environmental protection. Frequency multipliers are employed for the generation of low phase noise Ka band local oscillator signal. A high output power of 15dBm is maintained to drive the passive down conversion mixer with minimum conversion loss. The first component in the LO block is a 2GHz notch filter. The 4GHz input signal from the frequency synthesizer has a -20 dBc half frequency harmonic component. The 2GHz notch filter suppresses this half frequency component more than 50dB. The first active doubler converts 4GHz signal to 8GHz. A parallel-coupled BPF employed for harmonic suppression follows the active doubler. The subsequent stages comprise of an 8GHz to 16GHz passive doubler, 16GHz to 32GHz active multiplier and 32GHz Ka band BPF.

Two front-end receiver modules have been integrated and tested. The gain and frequency response of the two front-end receivers are measured on 04 port phase network analyzer (PNA). Figure 4(a) illustrates the simulated and measured gain of the two front-end receivers. It may be noted that the front-end comprises of seven MMICs and various passive planar structures. The gain and frequency response of the two front-ends is fairly identical. This exhibits the re-producibility of such front-end receivers using laser ablation process. The measured result shows an image rejection of more than 40dB is achieved. The simulated and measured input return loss of two front-end receivers is shown in Figure 4(b). The fabricated front-end receiver exhibits spurious free output spectrum. The 37GHz (-52dBm) signal is fed to the receiver input.



(a) (b)

Figure 4. Simulated and Measured Response of Two Ka Band Front-end Receivers

However, when compared with the simulated response, the measured results exhibit two issues in the front-end performance. Firstly, the gain of the front-end is 37dB which is 3dB lower than the simulated one. Secondly, the frequency response of the front-end is shifted 3GHz upwards as can be viewed in Figure 4. The reason for this gain reduction and frequency shift is deliberated. The geometric dimensions of the manufactured printed circuits of the two front-ends are measured on optical microscope and compared with the CAD layout file. The differences were within ± 2.0µm range. The simulation results confirm that such small differences cannot induce such a large frequency shift. It is assumed that the complex permittivity characteristics of the substrate are altered as a post-effect of laser ablation process. The preliminary literature survey reveals that for the duration of the laser pulse, the absorbed energy diffuses over the substrate [12]. This preferential energy absorption over the Teflon material may cause such effects. The change in permittivity causes mismatch inside the front-end which results in higher standing waves and degraded gain. In addition to this, the input return loss also degrades beyond 36GHz as shown in Figure 4(b). The other possible reason for the degraded gain could be the fact that the post laser ablation dissipation factor would be relatively higher than the specified one. The phenomenon of permittivity alteration due to laser structuring over the prescribed substrate is briefly reported in [13].

In order to validate the alteration in the complex permittivity due to laser ablation process, the Ka band image rejection BPF employed in the front-end receiver has been fabricated and tested separately. Ten samples of the same filter design have been fabricated with each process i.e. laser ablation and photolithography process. Figure 5(a) and (b) depicts the parallel-coupled BPF fabricated with photolithography and laser ablation process respectively. The post laser ablation defects such as diagonal line cuts can be viewed over the surface of the substrate in the Figure 5(b). The geometric dimensions of laser ablated filters are measured on optical microscope. It is noticed that the geometric dimensions of the fabricated filters exactly overlap the CAD layout of the filter supplied for manufacturing. This measurement ensures that the frequency shift in filter's response is not because of the manufacturing inaccuracies. Similarly, three BPF samples fabricated with photolithography process have been chosen for experimentation. The geometric dimensions of these sample BPFs are ensured before assembling and testing.

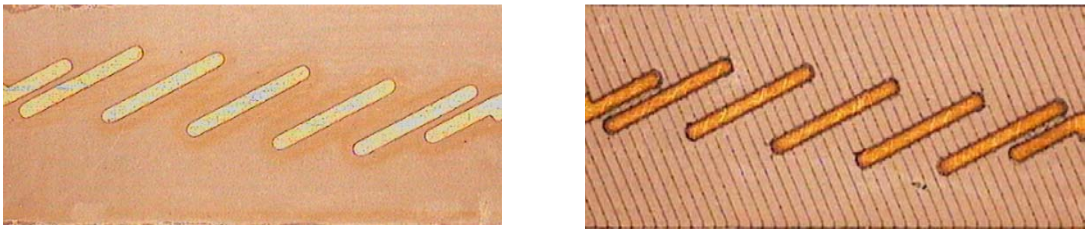
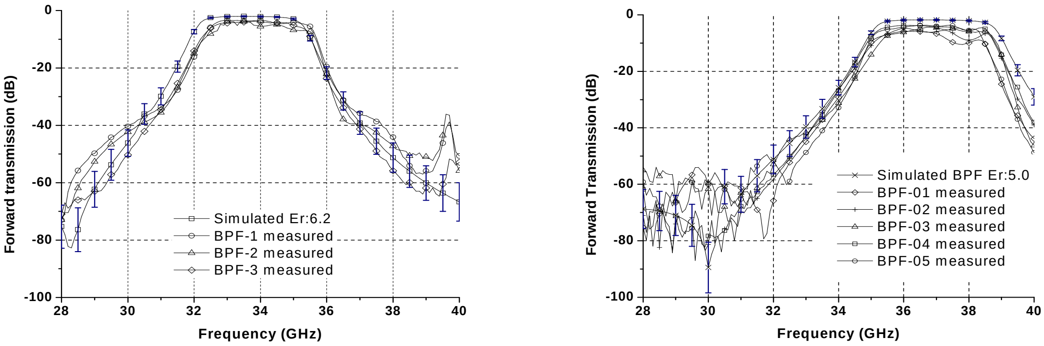

(a) (b)

Figure 5. Fabricated Ka Band BPFs (a) Chemically etched (b) Laser ablated

Three chemically etched filters have been assembled and tested. Measurements are carried out at PNA. The simulated response for the specified permittivity (E_r : 6.2) and the measured response of the three chemically etched filters are shown in Figure 6(a). The simulated and measured results are in good agreement. Further, five laser ablated filters have been assembled and tested. In order to precisely extract the measured filter's response, an in-house customized Through-Reflect-Line (TRL) calibration kit is produced. By employing TRL method, the fixture effects are removed from the measured results [14]. The de-embedded forward transmission responses of five fabricated filters and the simulated response with E_r=5 are shown in Figure 6(b). It is noticed that the measured response of the laser ablated filters matches the simulated response of the filter with E_r=5.0.



(a) (b)

Figure 6. Simulated vs Measured Response (a) Chemically etched (b) Laser structured

In order to visualize the deviation in the simulation and measured results, ± 10% y-axis error bar is added to the simulated response in Figure 6(a) and (b). Comparing the de-embedded response of the filters with the simulated response, a dip in the passband at 38GHz is observed. The fabricated filters are enclosed in 3.8mm wide metallic cavities. This dip in the passband response is possibly due to the presence of a waveguide dominant mode inside the channel at around 38GHz. The comparison of chemically etched and laser ablated filter's response indicates that the measured frequency shift is 3.05GHz. This frequency shift between chemically etched and laser ablated BPFs indicates a reduction in the permittivity of the laser ablated BPF. It is deduced that the effective E_r is reduced from 6.2 to around 5.0.

4. Proposed Design Method

It is well known from the microwave circuit theory that any alteration in the permittivity of the substrate modifies the characteristic impedance of the matched transmission lines. The visibility of this permittivity alteration is more pronounced when there are planar resonant structures in the design as in our case. The front-end comprises of three parallel-coupled BPFs (one at X band and other two at Ka band) and one 2GHz notch filter. A parallel-coupled BPF comprises of multiple quarter wave length coupled-line sections. In order to achieve the desired specifications on such substrates with the prescribed manufacturing process, one of the possible solutions is to characterize the substrate permittivity characteristics by using one of a permittivity measurement technique. Later, the design layout can be drawn employing the measured permittivity figures. Over the years, various methods have been proposed to characterize the complex permittivity of the substrate such as waveguide method, cavity resonator method, free space method etc [15, 16]. Each method has its own limitations and accuracy. However, there are two constraints to carry out such experimentation. Firstly, the associated test fixtures and equipment is required for each method. This consumes additional resources in terms of time and cost. Secondly, for the above mentioned permittivity test methods, the top and bottom copper cladding of the substrate must be removed for availability of sample under test (SAT). In the laser ablated printed circuit process, the top cladding is structured while the bottom layer is copper ground plane. However, if both the top and the bottom claddings are removed with laser ablation, then, this scenario does not reflect the actual printed circuit structure. Moreover, it is expected that the effect on complex permittivity of single side laser ablated and double side laser ablated SAT could be significantly different. Alternatively, the copper cladding of one side of the SAT can be chemically etched and later the copper cladding of the other side can be removed with laser ablation process. However, this complicates the SAT fabrication process.

A simplified method is proposed to extract the permittivity of a laser ablated printed structure. The permittivity of a laser ablated substrate can be extracted from the measured frequency response of a laser ablated parallel-coupled BPF in conjunction with a full-wave EM solver. The steps are as follows. A parallel-coupled BPF is designed for a dielectric constant specified by the substrate manufacturer and fabricated with laser ablation process. The measured results are compared with the simulated one. An iterative full-wave EM simulation is carried out by varying the dielectric constant to match the measured response of the BPF. The post laser ablated dielectric constant of the prescribed substrate is extracted using this method. The measured response of the laser ablated Ka band BPF given in Section IV is employed for this extraction. The extracted dielectric constant found out to be 5.0. In order to validate the accuracy of the extracted dielectric constant, an X-band parallel-coupled BPF is designed and fabricated on the same substrate. The BPF is designed for extracted dielectric constant (i.e. E_r: 5.0). The X-band is primarily selected for the reason that the coaxial connectors' discontinuity is lesser at this band and this result in a symmetric response of the TRL calibration kit used for the BPF de-embedding. The photograph of the X-band BPF is depicted in Figure 7(a). The simulated and measured results are shown in Figure 7(b). The same filter design is simulated for E_r: 6.2 (specified by the manufacturer) as well. The measured response of the BPF is in good agreement with the simulated response (simulated with extracted dielectric constant E_r: 5.0).

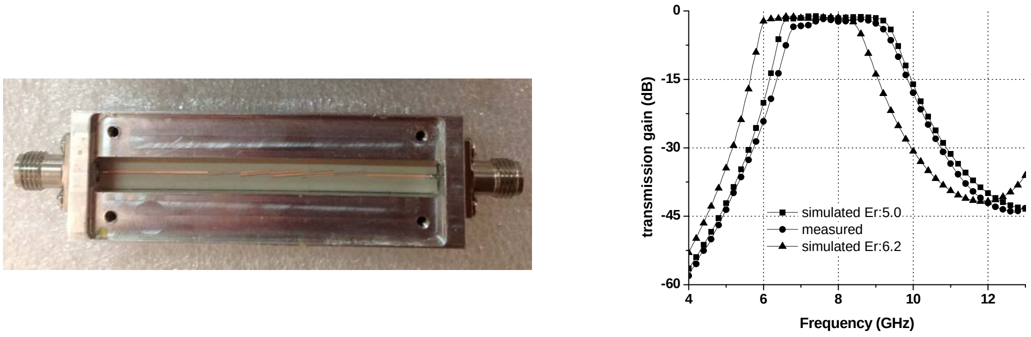


Figure 7. (a) X band band-pass filter (b) Simulated and measured response

4. Conclusion

The ceramic-polymer composite substrates are a good choice for MMW circuit design from various perspectives. Its higher dielectric constant and low dissipation factor makes it suitable for compact realization. The laser ablation process offers excellent geometric dimension accuracy with a high degree of repeatability which is best suited for prototyping phase and results in a high yield for mass production. In this paper, a compact Ka band front-end receiver module is designed, fabricated and tested on a low-cost ceramic-polymer composite substrate using laser ablation process. All the components of the front-end receiver operating from 2GHz to 34GHz are realized on a single substrate. This provides excellent ease of manufacturability and seamless integration. Two front-end modules have been integrated and tested. The measured gain and noise figure of the front-end is 37dB and 4.25dB respectively. However, it is experimented that the complex permittivity characteristics of such substrate are altered after the laser ablation process. This phenomenon of permittivity alteration is validated through the characterization of chemically etched and laser ablated Ka band parallel-coupled BPFs. In order to achieve the desired specifications on such substrates with the prescribed manufacturing process, a simplified method is proposed to extract the post laser ablated effective permittivity and the method is verified through experiments. The measured results obtained by employing the proposed method are in good agreement with the simulated one. It is intended that passive circuits shall be designed at MMW bands to analyze the method affectivity. Further, other substrate types with the prescribed printed circuit manufacturing technique may also be experimented.

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