

## Packaging approaches for GaN/Si SAW Band Pass Filters with Operating Frequencies above 5 GHz

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**Abstract.** This paper presents two packaging approaches for surface acoustic wave band pass filters (SAW-BPF) processed on GaN/Si and operating at frequencies above 5 GHz. One approach is based on a surface mount device (SMD) quad flat no-leads (QFN) ceramic package available off-the-shelf for applications up to few GHz. The other approach is based on quasi-wafer level packaging (quasi-WLP), using a PMMA cap and epoxy resin glue to cover only the sensitive area of the SAW-BPF. The two packages are evaluated using a coplanar waveguide transmission line (CPW-TL) as test vehicle. The ceramic SMD QFN package shows additional losses lower than 1 dB up to 6 GHz, while the PMMA quasi-WLP shows additional losses lower than 0.1 dB up to 30 GHz. SAW-BPFs with operating frequencies around 5.5 GHz are packaged using the two approaches and measurement data shows little effect on the main SAW-BPF parameters.

**Key-words:** band pass filters, ceramic package, coplanar waveguide, gallium nitride, packaging, PMMA, surface acoustic wave, surface mount device, wafer level packaging

### 1. Introduction

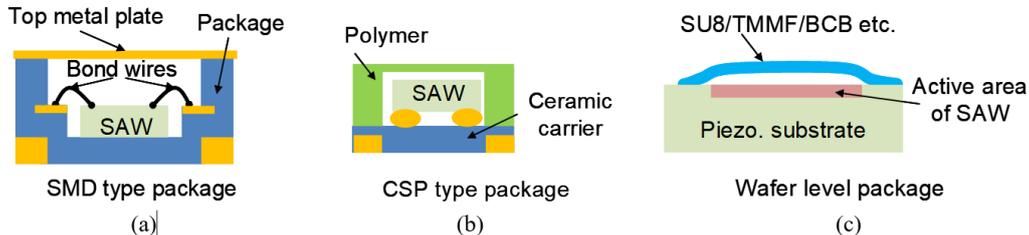
Packaging of electronic devices is a continuously developing engineering field whose complexity increases with the operating frequency of the device. The main purpose of packaging is to offer protection from environmental factors (mechanical shock, humidity, dust, scratching, gases etc.) that might affect the functionality of the device. Factors such as electrical, thermal and mechanical properties, as well as cost, footprint and operating frequency need to be taken into account, leading to a multidisciplinary approach to package design. Application requirements are a key aspect when choosing the appropriate combination of material, fabrication process, integration approach. For the low GHz domain there are a range of relatively mature packaging technologies available on commercial basis, due mainly to the mobile communications industry.

For higher frequencies it becomes increasingly difficult and custom packages become mandatory [1-2].

Surface acoustic wave (SAW) filters are used intensively in mobile communications for band selection filter banks due to their high quality factors and relatively low losses. Commercial manufacturers include TriQuint Semiconductor, Qorvo, Murata, Qualcomm, Vectron. These companies offer products operating up to 3 GHz and use ceramic Surface Mount Device (SMD) packages or Chip Scale Packages (CSP). The ceramic SMD technology is a widespread hermetic packaging solution, where the SAW filter chip is soldered in a ceramic housing and wire bonded to the case (Fig. 1 (a)). A top metal plate is used to seal the package [3]. This approach has proven to be successful up to 3 GHz, but the through package vias and wire bond parasitics can start to affect the SAW device response at higher frequencies. Also the package can be quite bulky compared to the initial chip size.

The CSP approach offers a smaller footprint compared to the SMD approach. In this case, the SAW device is soldered to a ceramic carrier and a polymer is used for encapsulation (Fig. 1 (b)). Through substrate vias are still required for efficient hermetic packaging [2].

Another packaging technique developed mainly for RF-MEMS (micro-electro-mechanical system) is the Wafer Level Packaging (WLP). Since SAW devices are processed on piezoelectric substrates and are based on micron and sub-micron interdigital transducers (IDTs), they are prone to some of the same problems as the RF-MEMS. A typical approach for WLP is shown in Fig. 1 (c). In this case thin layer dielectrics such as SU8, TMMF or BCB are used to cover only the sensitive part of the device. This is achieved by employing additional front-end processing steps such as thin-film deposition and localized etching [4].



**Fig. 1.** Common packaging solutions for SAW devices: (a) surface mount device (SMD) package; (b) chip size package (CSP); (c) wafer level package (WLP).

In order to evaluate the suitability of a specific packaging technology for a given device, the effect of the package on the main parameters needs to be estimated. In the case of microwave devices, the performance of the integrated device can be predicted either by measuring the key parameters of prototype samples, or by performing electromagnetic modeling of the 3D complex configuration of the packaged device.

In this paper two packaging approaches for SAW band pass filters (BPF) operating at frequencies above 5 GHz will be investigated. The SAW-BPFs are manufactured on GaN/Si substrate and consist of IDTs with 200 nm wide digits. This type of device was presented by the authors in [5].

The first approach is based on a commercially acquired ceramic Quad Flat No-leads (QFN) package. This is a SMD type package.

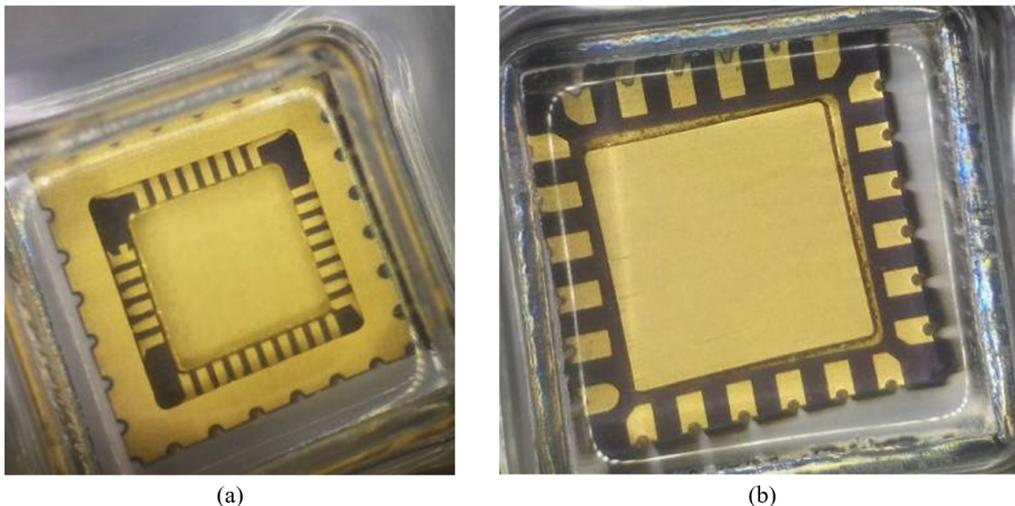
The second approach was first proposed by the authors in [6] and is based on the quasi-

Wafer Level Packaging of the SAW-BPF using a Poly(methyl methacrylate) (PMMA) cap. As a proof of concept, in [6] a 2.8 mm long  $50 \Omega$  coplanar waveguide transmission line (CPW-TL) was packaged and a comparison between measured and simulated data was provided. The main parameters of a packaged filter were presented as tabular data. The current paper will present the full S-Parameter measurement results before and after integration of the SAW-BPF.

Both packaging approaches will be tested first on a 2.8 mm long CPW-TL and then on SAW-BPFs.

## 2. Ceramic SMD QFN packaging approach

Quad Flat No-leads ceramic packages are a widespread standard for SMD hermetic packaging of devices operating up to 2-3 GHz. They offer protection against mechanical shock, humidity and have a good thermal behavior. When moving up to higher frequencies, they become quite an expensive solution due to the need to compensate the package effects, such as parasitic inductances of through package vias. Another issue is related to the relatively bulky size of the ceramic package. In order to package a surface acoustic wave band pass filter (SAW-BPF) with a functional area of about  $1 \times 2 \text{ mm}^2$  and operating frequency around 5.5 GHz, the most suitable ceramic package found off-the-shelf was a  $5.5 \times 5.5 \times 1.25 \text{ mm}^3$  QFN from NTK (<http://www.ntktech.com/>) with a cavity area of  $3 \times 3 \text{ mm}^2$ . The chip thickness considered was between  $500 - 750 \mu\text{m}$ , while the total cavity depth of the QFN package was 1 mm. The package has a total of 24 leads, with 6 dedicated to RF use up to 10 GHz. Manufacturer specifications indicate simulated losses of 0.5-0.7 dB per lead around 5.5 GHz for selected RF leads. The inside and backside views of the package are shown in Fig. 2. (a) and (b) respectively.



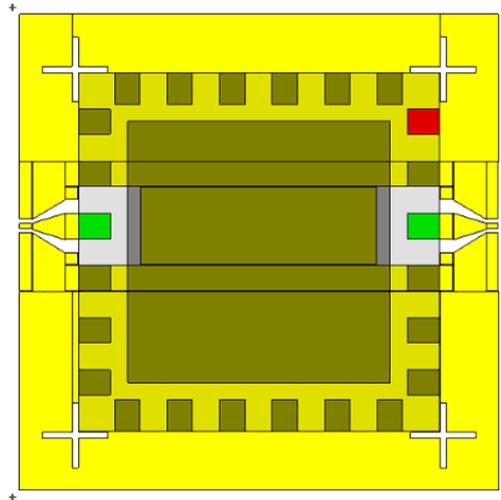
**Fig. 2.** SMD QFN package: (a) inside view of package; (b) backside of package.

In order to minimize the length of the wire bonds from the SAW-BPF to the package, coplanar waveguide transmission lines (CPW-TL) were added to the input and output of the filter, resulting in a final chip size of  $2.8 \times 2.8 \text{ mm}^2$ . The GaN/Si SAW-BPF design is based on the approach described in detail in [5].

For the packaging approach evaluation,  $2.8 \times 2.8 \text{ mm}^2$  CPW-TL chips with a characteristic impedance of 50 Ohm were designed and fabricated on the same wafer with the SAW BPFs.

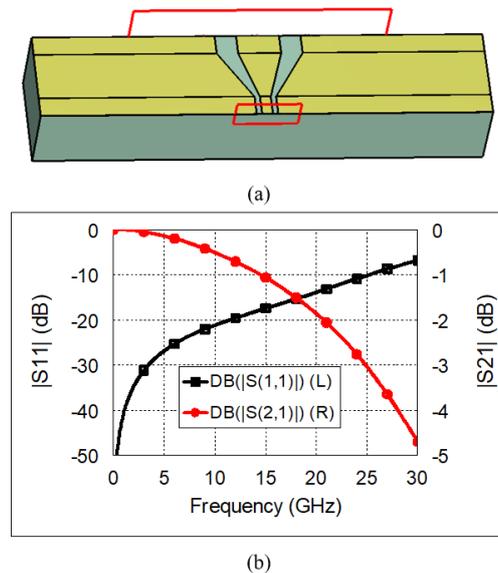
## 2.1. Microwave performance assessment of ceramic SMD QFN package

For measurement purposes, in order to fully characterize the QFN package, a dedicated holder was designed and fabricated. Fig.3 shows the layout of the holder designed to be fabricated on gold metallized Alumina of 650 micron thickness. The QFN package footprint is also shown. The integration is done using conductive silver epoxy on the backside ground of the QFN package and on the outer contact leads. The RF signal contacts are indicated in green. A tapered CPW transmission line segment is used to connect the 0.4 mm width/gap of the QFN pads to the 0.05-0.1-0.05 mm wide gap-signal-gap needed for proper contact of the VNA G-S-G probes (150 micron pitch), while also ensuring a close to 50 Ohm matching. The final size of the holder ceramic is  $7.5 \times 7.5 \text{ mm}^2$ .



**Fig. 3.** Layout of ceramic test fixture for epoxy bonding of ceramic QFN package.

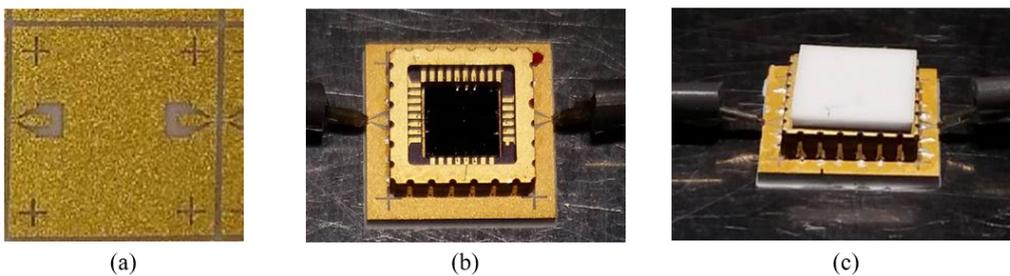
For the design of the tapered CPW-TL segment, an electromagnetic model was developed in the CST Microwave Studio software package ([www.cst.com](http://www.cst.com)). CST Microwave Studio (MWS) is a highly versatile 3D full-wave electromagnetic simulation software. It offers a number of solvers (time domain, frequency domain, eigenmode, integral equation solver, multilayer solver, asymptotic solver) based on a variety of methods like the Finite Integration Technique (FIT), the Finite Element Method (FEM), the Method of Moments (MoM). It can handle millions of mesh cells (it supports tetrahedral, hexahedral, surface and multilayer meshing) and offers accurate results over wide frequency ranges. A 3D view of the model is shown in Fig. 4 (a). The simulated S-parameter results for a 0.5 mm long taper are given in Fig. 4 (b). Around 5 GHz the losses added by the tapered CPW-TL are lower than 0.2 dB.



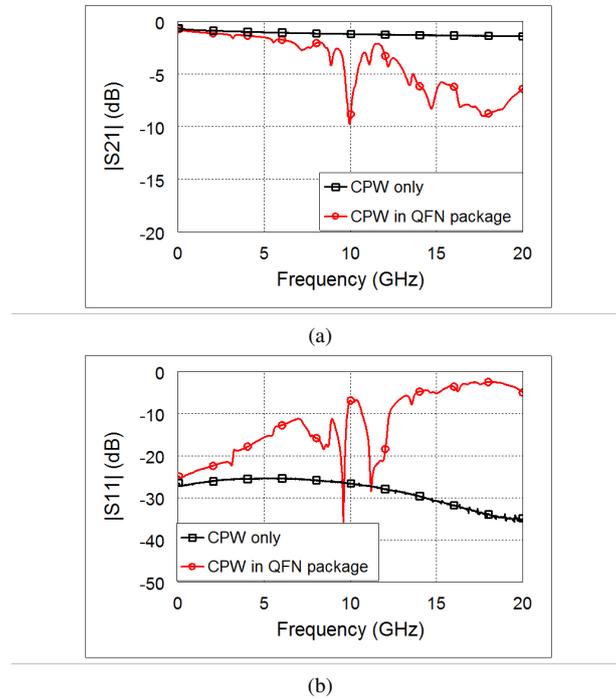
**Fig. 4.** (a) 3D view of the electromagnetic model developed in CST Microwave Studio for the tapered CPW-TL; (b) simulated S parameter results.

The integration procedure consists of dicing the ceramic holder (Fig. 5 (a)), silver epoxy integration of the SMD QFN packaged device on the holder (Fig. 5 (b)), followed by gluing a metallized lid (facing down) over the QFN package (Fig. 5 (c)).

The 2.8 mm long 50 Ohm CPW-TL was diced and measured on-wafer before and after packaging. The measurements were performed using a Anritsu Vector Network Analyzer with on wafer probing system and 150  $\mu\text{m}$  pitch ground-signal-ground probes. A short-open-load-thru calibration (SOLT) was performed for 1601 measurement points, an average of 4 measurements per point and an intermediate frequency of 1 kHz. As it was expected, the QFN packaging adds extra insertion losses. The presence of parasitic resonances around 10 GHz and higher insertion loss above this frequency can be noticed. Around 5.5 GHz (the central operating frequency of the SAW-BPF – see below) the packaging effect is much smaller.



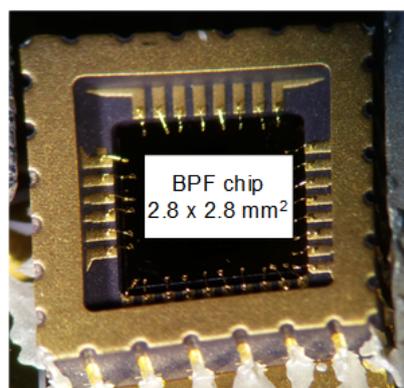
**Fig. 5.** SMD QFN packaging for microwave performance assessment: (a) fabricated ceramic test fixture; (b) GaN/Si chip wire bonded inside QFN package; (c) QFN package with metallized ceramic cap.



**Fig. 6.** Comparison of S parameter measurement results for the standalone and the QFN packaged CPW-TL: (a) transmission parameter; (b) reflection parameter

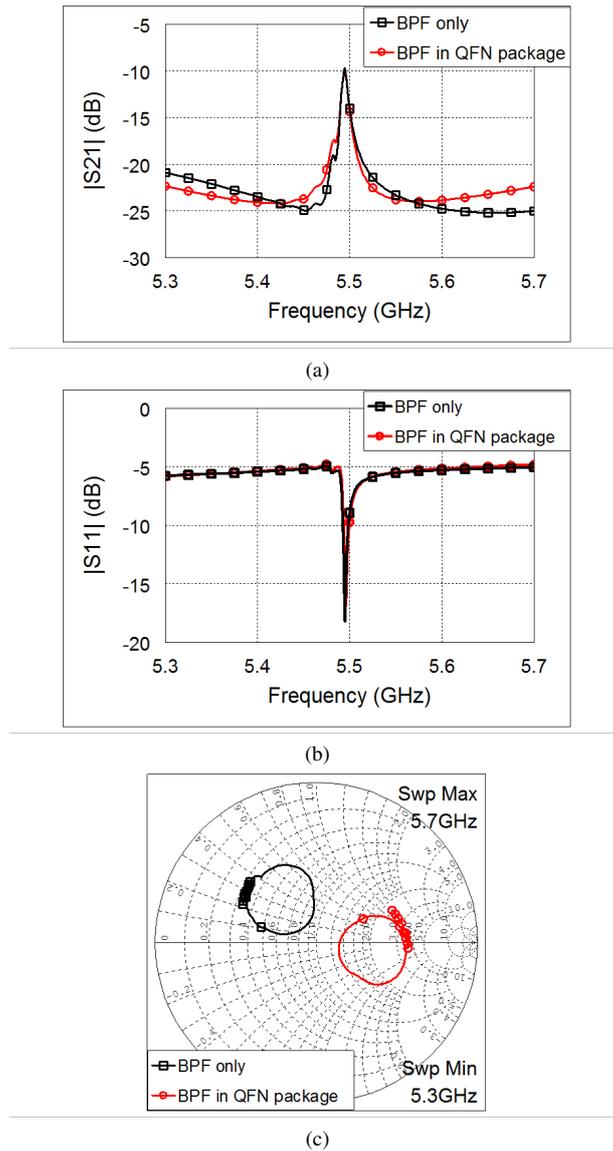
## 2.2. SAW-BPF integrated in ceramic SMD QFN package

A filter sample processed on GaN/Si wafer acquired from the NTT-AT Japan provider was integrated in a QFN ceramic package, acquired from NTK, using the procedure described in Section 2.1 (Fig. 7). The measurement results before and after packaging are shown in Fig. 8 and summarized in Table 1.



**Fig. 7.** Photo of GaN/Si SAW-BPF chip integrated in commercial SMD QFN ceramic package.

The results show a successful integration with very little influence of the package on the magnitude of the insertion and reflection losses (Fig. 8 (a)-(b)). A change in the reactance corresponding to the effect of bonding and packaging can be noticed on the Smith chart shown in Fig. 8 (c). No changes are observed regarding the central frequency (defined as the maximum value of the S21 parameter) or the 3 dB bandwidth.



**Fig. 8.** Comparison of S-parameter measurement results for the standalone and QFN packaged SAW-BPF: (a) S21 parameter; (b) S11 parameter; (c) S11 parameter plotted on the Smith chart

**Table 1.** Comparison of main parameters for packaged and un-packaged SAW-BPF using a ceramic QFN package

Filter Parameter	Initial chip	Ceramic QFN package
Insertion losses	9.72 dB	9.84 dB
Return loss	18.25 dB	16.9 dB
Out of band rejection	15.5 dB	14.35 dB
3dB bandwidth	7.7 MHz	7.7 MHz
Central frequency	5.495 GHz	5.495 GHz

### 3. PMMA quasi-Wafer Level Packaging

Various solutions for Wafer Level Packing have been proposed in literature [4]. But these solutions tend to remain purely academic ones, since the additional processes needed to implement the WLP are either too expensive or introduce unwanted complexity in the device fabrication.

An alternative solution would be a quasi-WLP approach using a machined or molded cap to cover only the sensitive area of the device. In combination with an epoxy glue, this solution can offer a cheap alternative, more easily implemented in an industrial setting.

For the SAW-BPF working at frequencies higher than 5 GHz, the cap material and epoxy glue need to be simulated electromagnetically in order to estimate their effect on the CPW-TL used to feed the SAW-BPF.

A low permittivity, low loss, mechanically and thermally robust material is needed for the cap. Poly(methyl methacrylate) (PMMA) is a material with a relative permittivity between 3.06–3.92 and a loss tangent around 0.03–0.05 for the low GHz frequency range [7]. The material is widely available, has a melting point of 160°C and is easy to process using manual or computer controlled cutting tools. These properties make it an attractive choice for the proposed packaging approach.

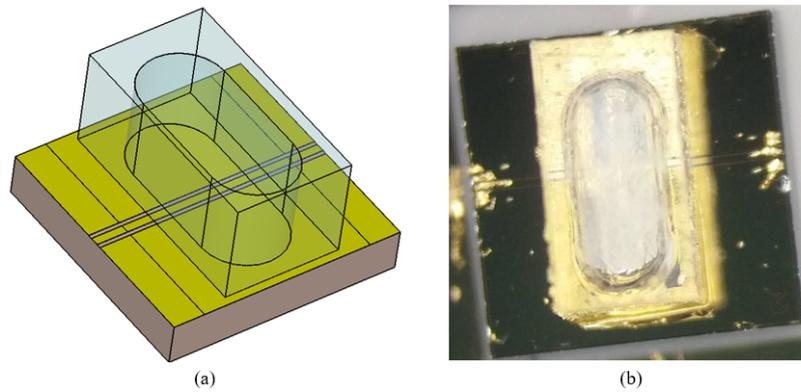
A common resin epoxy glue (reaction product: bisphenol-A-(epichlorhydrin), hardener: 4-tert-Butylphenol; 1,3-Cyclohexanedimethanamine) was chosen to integrate the cap ( $\epsilon_r \sim 3.5$ ) [8-9].

#### 3.1. PMMA quasi-WLP microwave performance assessment

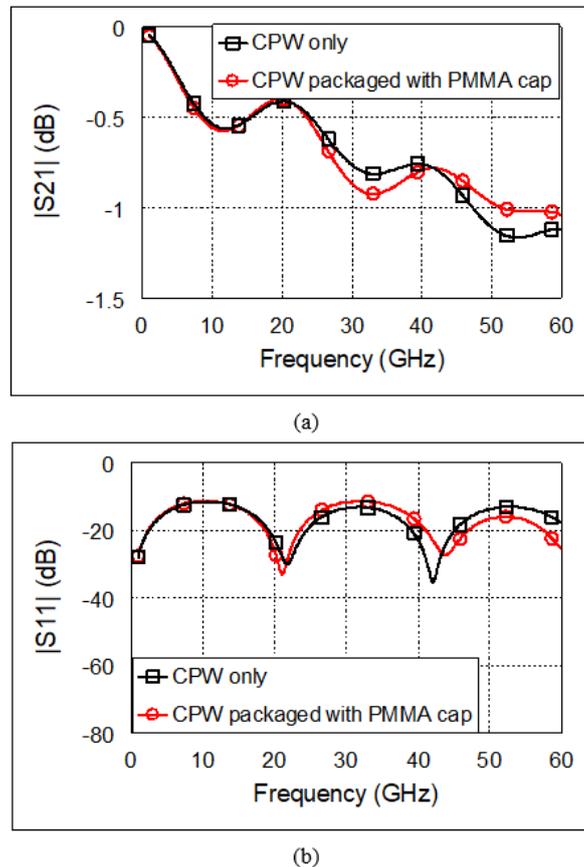
For the preliminary evaluation of the performances of the quasi-WLP, a 3D electromagnetic model of the PMMA cap was developed in CST Microwave Studio. A 3D view of the model is shown in Fig.9 (a) and it is an accurate representation of the fabricated PMMA cap glued on top of a GaN/Si chip (Fig.9 (b)).

The PMMA cap is placed on top of a 2.8 mm CPW-TL (gap-signal-gap of 50-100-50  $\mu\text{m}$ ). The epoxy glue was also included in the electromagnetic model [6]. After parametric simulations, the exterior size of the cap resulted as 2.7x1.4 mm<sup>2</sup>, with a wall thickness of 0.2 mm and a total height of about 1 mm. The cavity was designed for processing with a 1 mm diameter cutting tool.

The simulated S parameters for CPW only and CPW packaged with PMMA cap are presented and compared in Fig.10. Only small differences can be noted so it can be estimated that this packaging approach will not affect the frequency response of the packaged microwave circuit. The frequency response ripple is due to the fact that the CPW characteristic impedance is slightly different from 50 ohm.



**Fig. 9.** (a) 3D electromagnetic model of CPW-TL with PMMA quasi-WLP; (b) Photo of the fabricated PMMA cap glued on top of a GaN/Si chip.

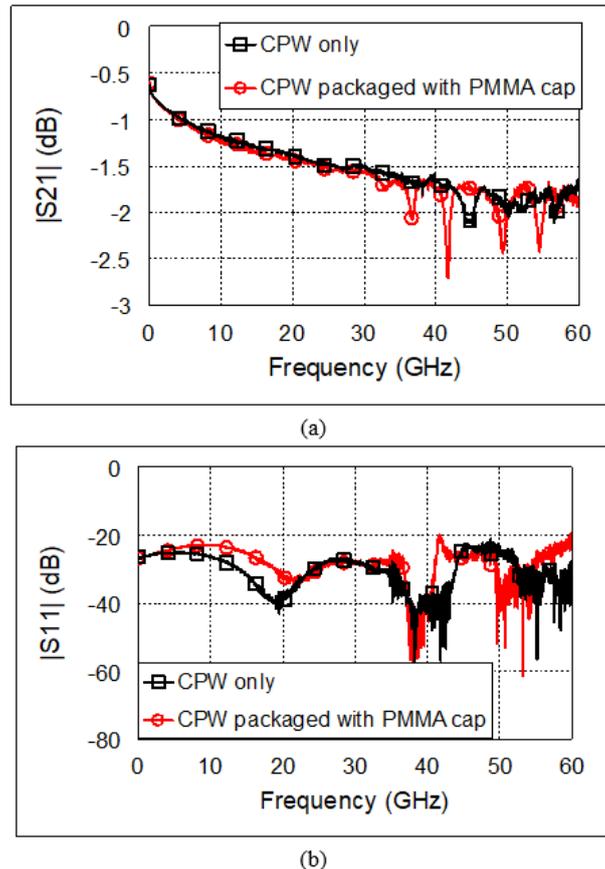


**Fig. 10.** Comparison of S parameter simulation results for the standalone and the PMMA quasi-WLP packaged CPW-TL: (a) transmission parameter; (b) reflection parameter.

A common commercial grade PMMA was acquired and machined to the dimensions presented above and integrated using the epoxy resin glue.

For the packaging approach evaluation,  $2.8 \times 2.8 \text{ mm}^2$  CPW-TL chips with a characteristic impedance of 50 Ohm were designed and fabricated on the same wafer with the SAW-BPFs. The GaN/Si wafer was acquired on commercially basis from EpiGaN in Belgium. [6]. The wafer was diced using a diamond saw.

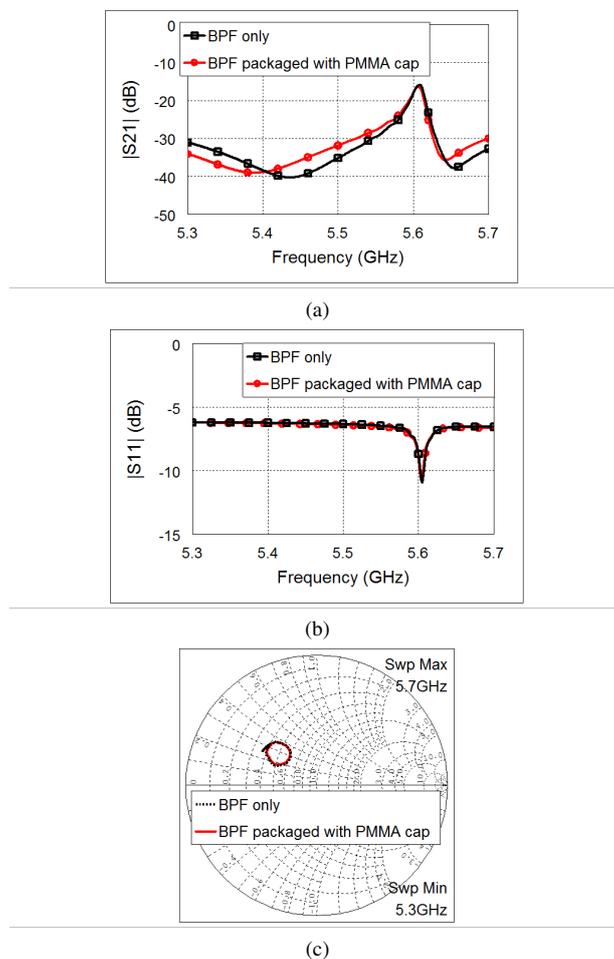
The CPW-TL structure was characterized on wafer using a Vector Network Analyzer and the SOLT calibration technique. A comparison of S parameter measurement results for the GaN/Si chip with the 2.8 mm long CPW-TL with and without the PMMA cap is shown in Fig. 11 (a) and (b). It can be noticed that this packaging approach has an insignificant effect on the circuit performances up to 30 GHz. The influence of the PMMA cap (fixed with resin glue) starts to show at frequencies over 30 GHz, where some resonances add up to 1 dB loss.



**Fig. 11.** Comparison of S parameter measurement results for the standalone and the PMMA packaged CPW-TL: (a) transmission parameter; (b) reflection parameter.

### 3.2. PMMA quasi-WLP of a SAW-BPF

A SAW-BPF chip processed on a wafer acquired from the EpiGaN was packaged using a PMMA cap. The measurement results are shown in Fig. 12 (a)-(c) and a comparison of the main SAW-BPF parameters before and after packaging is given in Table 2. The central operating frequency of the SAW-BPF fabricated on EpiGaN substrate is a bit higher than on the substrate provided by the Japanese company NTT. The package itself adds only around 0.5 dB losses and almost no effect on the S11 parameter can be noticed. Since no bond-wires are used, no change in reactance occurs (see Fig. 12 (c)).



**Fig. 12.** Comparison of S-parameter measurement results for the standalone and PMMA packaged SAW-BPF: (a) S21 parameter; (b) S11 parameter; (c) S11 parameter plotted on the Smith chart

**Table 2.** Comparison of main parameters for packaged and un-packaged SAW-BPF using the PMMA quasi-WLP

	Initial chip	PMMA quasi-WLP
<b>Insertion losses</b>	15.9 dB	16.44 dB
<b>Return loss (S11)</b>	10.9 dB	10.7 dB
<b>Out of band rejection</b>	24 dB	23 dB
<b>3dB bandwidth</b>	16.5 MHz	17.7 MHz
<b>Central frequency</b>	5.61 GHz	5.61 GHz

## 4. Conclusions

Two packaging solutions for SAW based band pass filters processed on GaN/Si substrate, with operating frequencies over 5 GHz were presented.

The first packaging approach is based on integrating the filter chip inside a commercially available QFN ceramic package with outer dimensions of 5.5 x 5.5 x 1.25 mm<sup>3</sup>. The chip is wire bonded inside the package and the package is then bonded using conductive epoxy on a dedicated ceramic holder, for testing purposes. Metalized ceramic lids were also fabricated and attached to the QFN package using silver epoxy resulting in a hermetic package.

For the second packaging solution, a PMMA cap is used to protect only the sensitive part of the circuit (wafer level packaging). The approximate exterior size of the cap is 2.7x1.25 mm<sup>2</sup>, with a wall thickness of 0.2 mm and a total height of about 1 mm.

Both packaging solutions were evaluated using a 2.8 mm long CPW-TL processed on the same wafer as the SAW-BPFs. The results showed that the ceramic SMD QFN package is usable up to about 6 GHz, with an increase of insertion losses of less than 1 dB.

The PMMA quasi-wafer level packaging approach eliminates the need of wire-bonding and shows an increase of insertion losses lower than 0.1 dB up to 30 GHz. GaN/Si SAW-BPFs operating at frequencies higher than 5 GHz were packaged using the two approaches, with measurement results showing added losses less than 1 dB, with no major influence on other performances.

The quasi-WLP PMMA approach has a much lower cost compared to the ceramic SMD QFN solution and better wide band performances. Unlike traditional packages with thru substrate vias, it doesn't introduce additional parasitics and keeps the chip area small. The packaged chip can easily be wire bonded or probed directly on-wafer.

The extremely low losses added by the quasi-WLP PMMA up to millimeter wave frequencies, as well as the low cost and easy manufacturing make this a viable solution for SAW-based band pass filter encapsulation with operating frequencies higher than 5 GHz.

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