Development of temperature-stable RF filters on composite substrates based on a single crystal $LiTaO_3$ layer on Silicon

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ABSTRACT

SAW devices are widely used for radio-frequency (RF) telecommunication filtering and the number of SAW filters, resonators or duplexers is still increasing within the RF stages of cellular phones. Therefore, a strong effort is still dedicated to reduce as much as possible their sensitivity to environmental parameter and more specifically to temperature. In this paper, we develop acoustic filters based on Piezoelectric-On-Insulator (POI) wafers, i.e. on wafers combining thinned (YX*l*)/42° Lithium Tantalate thinned layer and on (100) Silicon wafers. The leading idea consists in impeding the thermal expansion of the piezoelectric material using the silicon limited thermal expansion of silicon. A drasmatic TCF reduction of the TCF is observed for all tested devices, allowing to reduce the thermal drift of the resonators down to a few ppm.K^{-1} within the standard temperature range with L-band filter characteristics on-line with usual RF requirements.

INTRODUCTION

The development of new generations of telecommunication wearable setups requires more and more front-end devices and modules. Radio-frequency (RF) communication particularly exploits multiple bands and needs data rate capabilities on line with the consumer demands. The simultaneous operation of all these bands yields among others the multiplication of RF filters to segregate standards. The preferred solution in that purpose is still based on Surface Acoustic Wave (SAW) principles and devices because of their unique spectral qualities (insertion loss, rejection, group delay, etc.), design flexibility and compactness for L and S bands. Although routinely exploited today, the use of single crystal substrates, typically Lithium Tantalate ($LiTaO_3$) and Lithium Niobate ($LiNbO_3$), is facing a deadlock as the intrinsic stability of those substrates is far to be adapted for modern telecommunication challenges. Actually, the above mentioned band multiplication imposes the filter to be very low sensitive to temperature as the filtering operation must be achieved in usual temperature range (-40/+85°C) without failure. The absolute temperature coefficient of frequency (TCF) of these filters must be typically smaller than 10 ppm.K^{-1}. Such low TCF together with excellent filter shape will enable for example carrier aggregation capability for next SAW multiplexer generations.

In this paper, we present a new generation of substrates which addresses the above mentioned demand and provides a unique solution for temperature-stable filter with excellent spectral qualities. The idea consists in using engineered substrates including a single crystal piezoelectric top layer on a high crystal quality substrate with very low thermal expansion properties The Piezoelectric-On-Insulator (POI) layer structure provides a breakthrough solution for addressing modern filter challenges on an extended range of specifications.

Although the use of composite (dispersive) substrates may generate specific difficulties for managing mode contributions, different ideas are proposed to keep the interest of high quality single-crystal-based SAW filters with the advantages of temperature compensation combining in particular $LiTaO_3$ with (100) high resistivity Silicon. In a first section of the presentation, we give details concerning the manufacture of said thick (15 to 30 µm) $LiTaO_3$ piezoelectric layers bonded to Silicon using direct molecular bonding techniques. A next section shows characterization results of SAW test vehicles built on these substrate. We then introduce some design principle and concepts to manage the spectral behavior of single-port resonators used as impedance element in SAW-ladder filters. These principles are implemented for narrow band (less than 1%) and intermediate band (near 3%) filters at frequencies between 1 and 1.6 GHz. The filter measurements are exposed, showing the quality of the device operation concerning in-band losses, rejection and spectral purity (about 3 dB insertion loss – IL – with more than 40 dB rejection) and of course the very high thermal stability of these filters in the above-mentioned thermal operation range (near Quartz-crystal-based SAW device stability). As a conclusion, we discuss the interest of such filters for space industry needs and its possible use for any SAW application replacing usual single-crystal-substrate-based solutions.

PIEZO-ON-INSULATOR – POI – WAFERS

The idea consisting in the combination of thick substrate exhibiting a low Thermal Coefficient of Expansion (TCE) with thinned piezoelectric top layers has been investigated by several groups at the end of the passed century [1,2,3], when technology was mature enough to allow for such developments. As explained in Introduction, the main motivation for such a development is to reduce the TCF of surface waves and filters based on that principle by impeding thermal expansion of the piezoelectric propagation support (Fig. 1). Two approaches were then promoted, respectively based on the so-called Smart-Cut™ [4] and the Smart-Stacking™ [5] approaches. In this paper, we focus on the later one which has been implemented for the proposed demonstration (Fig. 2). First, one has to precise the notions of thick and thinned here relatively to the SAW wavelength. Actually, we consider a thick substrate when it thickness ranges in the 100 wavelengths λ or more whereas thinned (or thin) will correspond to about or less than 10 λ in the present context.

When computing the thermal sensitivity of SAW devices according the celebrated Campbell & Jones method [6], it turns out that the TCF is composed at first order of a contribution relative to elastic properties and another contribution due to thermal expansion. In the case of leaky-SAW (LSAW) on $LiTaO_3$, one of the preferred solutions for cell phone filters, the TCE is quite large and responsible for more than a half of the resulting TCF (between -40 and -30 $ppm.K^{-1}$). Therefore, the idea consists in artificially suppressing the TCE part of the TCF by combining $LiTaO_3$ with a low TCE material, such as Silicon Oxide (TCE<1.5 $ppm.K^{-1}$), Sapphire (TCE~4 $ppm.K^{-1}$) or Silicon (TCE~2.5 $ppm.K^{-1}$) according various handbooks of physics (see for instance [7]). Note that thermo-differential effects also modify the effective thermo-elastic properties of the piezoelectric plate, reducing TCF of SAW propagation on such composite wafers, as shown in [3] for instance. However, when the top piezoelectric plate is thick enough (~10 λ), the main effect is actually due to the substrate-induced TCE reduction and appears controllable.

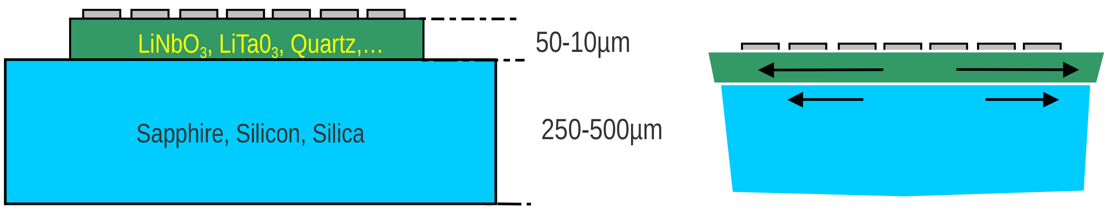


Fig. 1. General pricniple of a composite wafer combining a low TCE substrate impeding a top piezoelectric plate to thermally expand, limiting its sensititivty to temperature changes

The calculation of the temperature coefficient of phase velocity (TCV) can be easily computed without accounting for thermal expansion. In the case of LSAW on single-crystal (YX*l*)/42° $LiTaO_3$, the computation indicates a TCV of only -9.0 $ppm.K^{-1}$, whereas the TCF which integrates the material thermal expansion is estimated at -30 $ppm.K^{-1}$. This means a part of the TCF due to thermal expansion of more than 70%, which partly explains the results of the on-trench measurements, considering a Si thermal expansion of 2 to 3 $ppm.K^{-1}$ which yields a TCF in the -12 $ppm.K^{-1}$ range. One can therefore consider that even for a 10 λ thick $LiTaO_3$ plate, a 100 λ thick Silicon substrate actually imposes its in-plane thermal expansion and allows for reducing the TCF.

As stated above, wafer bonding technologies have experienced significant improvement in recent years and can be efficiently implemented to provide composite wafers meeting industrial requirements. The manufacturing principle of such wafers is shown in Fig. 2. A Silicon wafer and a $LiTaO_3$ wafer with similar shape (bow and warp) and total thickness variation (TTV) at state-of-the-art are prepared to allow for hydrophilic bonding [5, 6]. This operation requires an accurate control of surface preparation conditions (Roughness, flatness, particles free, chemical activation, etc.). Process conditions must be carefully engineered due to the large TCE mismatch between (100) Silicon and (YXl)/42° $LiTaO_3$. The Lithium Tantalate wafer then is thinned down to the expected final thickness. A final surface polishing is applied to reach the SAW grade quality, leading to standard crystal and surface characteristics used for SAW device industrial manufacturing. An example of 150 mm diameter (YX*l*)/42° $LiTaO_3/SiO_2/Si$ POI wafer is reported in Fig. 3.

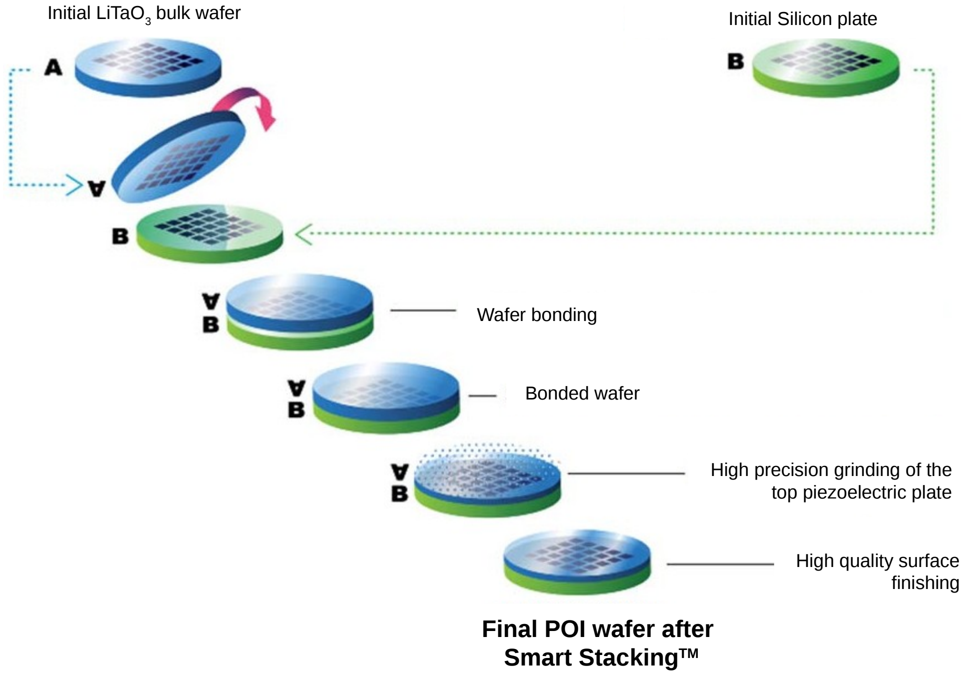


Fig. 2. Smart-Stacking® principle applied to piezoelectric-on-insulator – POI – wafers

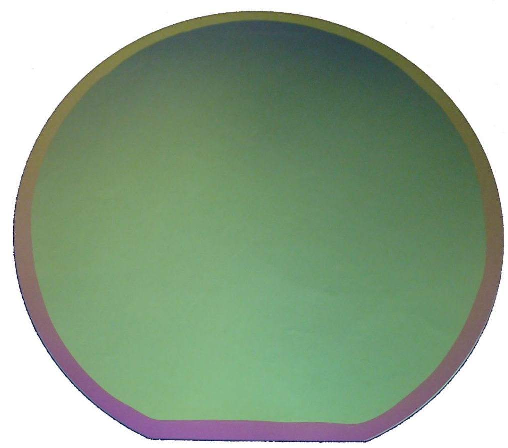
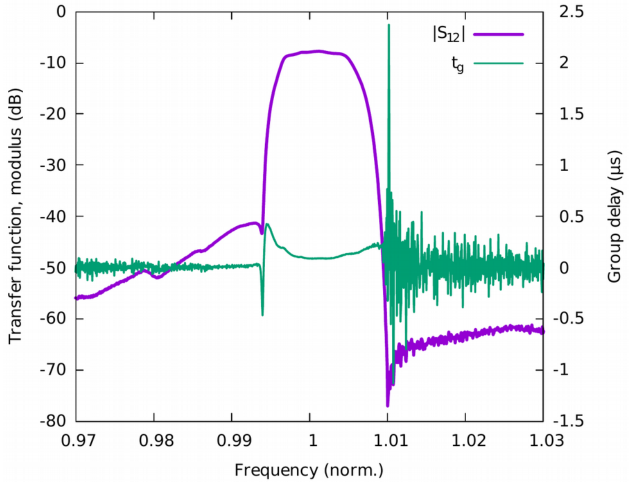


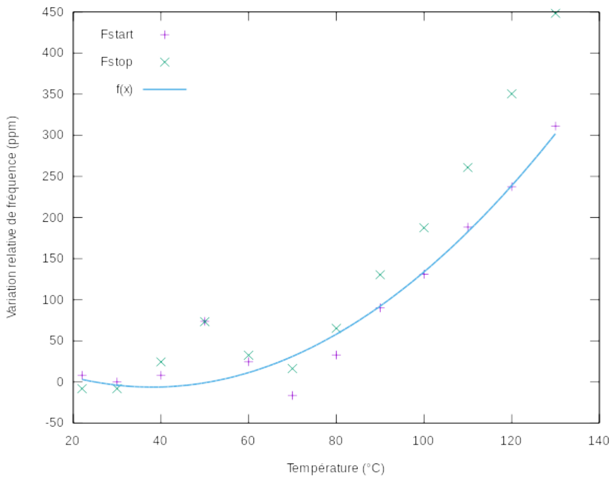
Fig. 3. Very high quality full wafer $LiTaO_3$ film transfer, 150 mm diameter wafer with SAW grade surface finishing

FIRST EXAMPLE OF A RF FILTER ON POI

A first example of filter is shown in . The operating frequency cannot be disclosed here for confidentiality reason. The POI wafer was composed of a 18µm-thick (YX*l*)/42° $LiTaO_3$ layer bounded onto a (100) Silicon wafer via a 500nm-thick SiO_2 layer. This filter corresponds to a 0.4% relative bandpass for which the mode is exhibiting a coupling much larger than required and therefore restrained by artificially increasing the static capacitance. As a consequence, 50 Ω impedance matching was not achievable, thus requiring a L-C matching network to be added to the filter terminations. IL were found in the vicinity of 8 dB and far rejection better than 40 dB, as shown in Fig. 4. The most remarkable point of this device is its thermal stability which was found almost temperature compensated near room conditions, with linear and quadratic TCFs comparable to quartz device values: $-0{,}9 < TCF_1 < 1$ ppm.K^{-1}, $+30 < TCF_2 < +36$ ppb.K^{-2}.



(a)

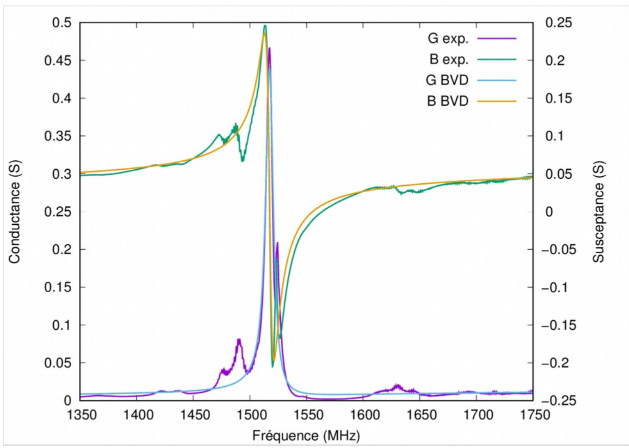


(b)

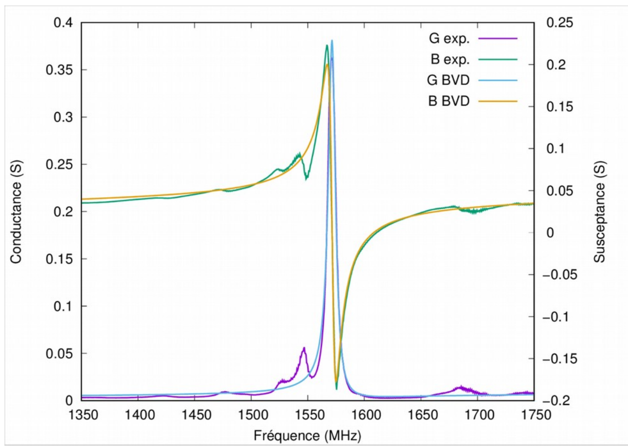
Fig. 4. 0.4% relative bandpass filter (a) Wide band transfer function $|S_{12}|$ (b) thermal sensitivity of the filter comparable to Quartz device one but with a positive curvature opposite, proper to $LiTaO_3$/Si substrates

GPS FILTER DEVELOPMENT

The second example of SAW filter developed on this type of wafer is corresponding to GPS applications and more precisely to L1 encoding band filtering. It is also based on a SAW-ladder architecture. Here again, we had to restrain the coupling to meet the 3% relative band specification as the "natural" capability of the structure would yield a 4,5 % relative band. Non synchronous resonators then have been considered in that purpose. The POI wafer was composed of a 30µm-thick (YXl)/42° $LiTaO_3$ layer onto a standard 650µm-thick Si wafer bounded via a 500nm-thick SiO_2 interlayer.



(a)



(b)

Fig. 5. Typical measurements of parallel and series resonators priori to the final design of the GPS filter, characterization of the main resonator and mode properties using a Butterworth – Van Dyke equivalent circuit and mixed matrix model (a) parallel resonator (b) series resonator

Before finalizing the filter design, a first characterization work has been performed to determine actual SAW properties. Series and parallel resonators have been manufactured and their electrical responses were fitted using a Butterworth – Van Dyke equivalent model prior to mixed matrix parameter evaluation (see results in Fig. 5 and 1). We have observed reproducible results for most tested resonators but also parasitic modes to be controlled in the final design.

Resonator type	Velocity (m.s^{-1})	f_{res} (GHz)	$f_{antires}$ (GHz)	Coupling k_s^2 (%)	Q_{BVD}	$\lvert R_{cc} \rvert$ (%)
R#1	3905,1	1,517127	1,554586	5,00	464	11,31
R#2	3934,8	1,56767	1,605368	4,87	605	11,23

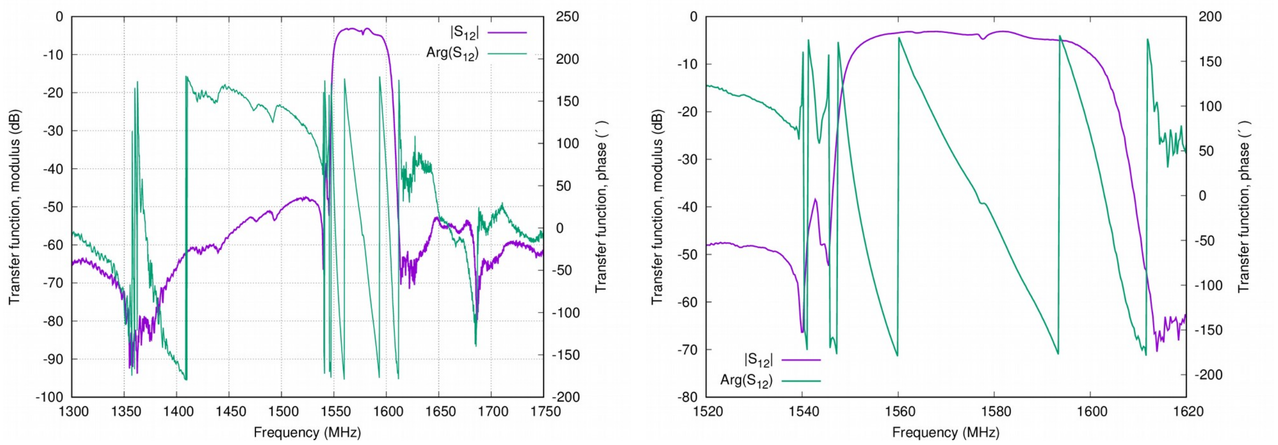
Table 1. Best fit of the Butterworth – Van Dyke equivalent circuit and mixed matrix model of the series and parallel resonator, evaluation of the mode properties and derivation of reflection coefficient in short circuit mode, values averaged considering 10 resonator measurements

The final design of the filter is based on 4 π-cells cascaded in series to achieve the targeted rejection. The filter was designed to operate with 50 Ω input/output impedance matching, single ended connection. Typical IL are found near 3.5 dB typical with a -3dB Filter bandpass near 45 MHz and a typical far field rejection of 45 dB. The device is capable to enter a 3.0×3.0 mm² ceramic Surface Mount Package (SMP), although the foot-print of the initial version was larger. Table 2 summarizes the main characteristics of the filter based on tip-probing measurements. Next step will consist in setting similar data for SMP-conditioned devices. The temperature sensitivity of the filter has been measured and found better than -9 ppm.K^{-1}, with a clear difference between low and transition band as shown in Fig. 8.

Parameter	Units	Minimum	Typical	Maximum
Center frequency (at 1 dB)	MHz	1574.42	1575.42	1576.42
Minimum insertion loss	dB	3.4	3.7	4.0
Band pass (3 dB)	MHz	45	46	47
Attenuation < 1.45 GHz	dB	45	50	55
Group delay variation (3 dB)	nsec	50	60	80
In-band ripple (at 1.5 dB)	dB	1.0	1.35	1.7
Wide band rejection	dB	40	45	50
Operating temperature range	°C	-40		+85
TCF absolute value*	ppm.K^{-1}	-11.0	-9.0	-7.0
Input – Ouput impedances	Ω	40	50	60
Reflected power (translated from VSWR)	dB	-8 (2.0)	-6.5 (2.5)	-5 (3.0)

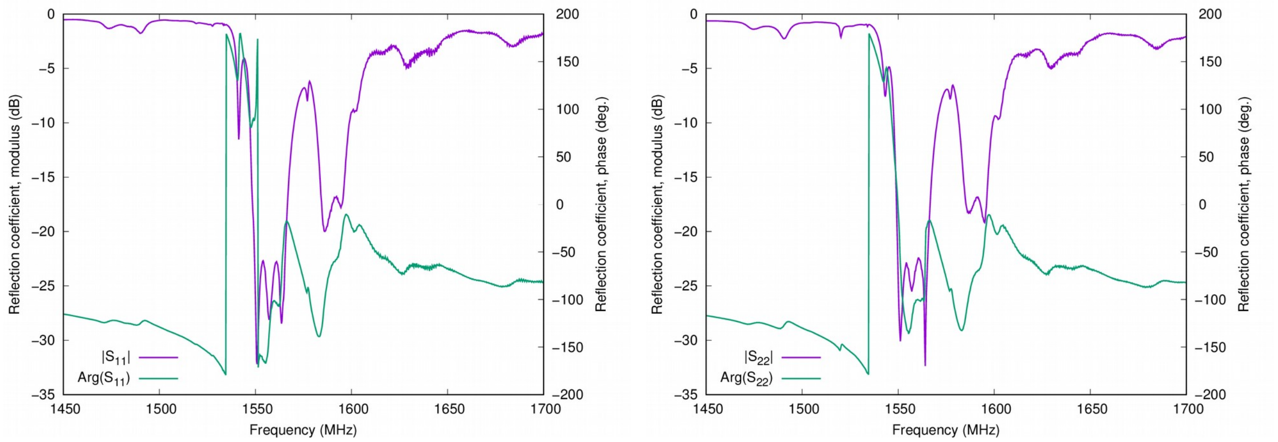
Table 2. Typical characteristics of the GPS filter developed to illustrate the interest of POI for RF SAW filters

*assuming a linear temperature-frequency dependence $f(T)=f_0\times(1+TCF_1\times(T-T_0))$ with TCF_1 the linear temperature coefficient of frequency, T_0=25°C and f_0 central frequency at T_0.

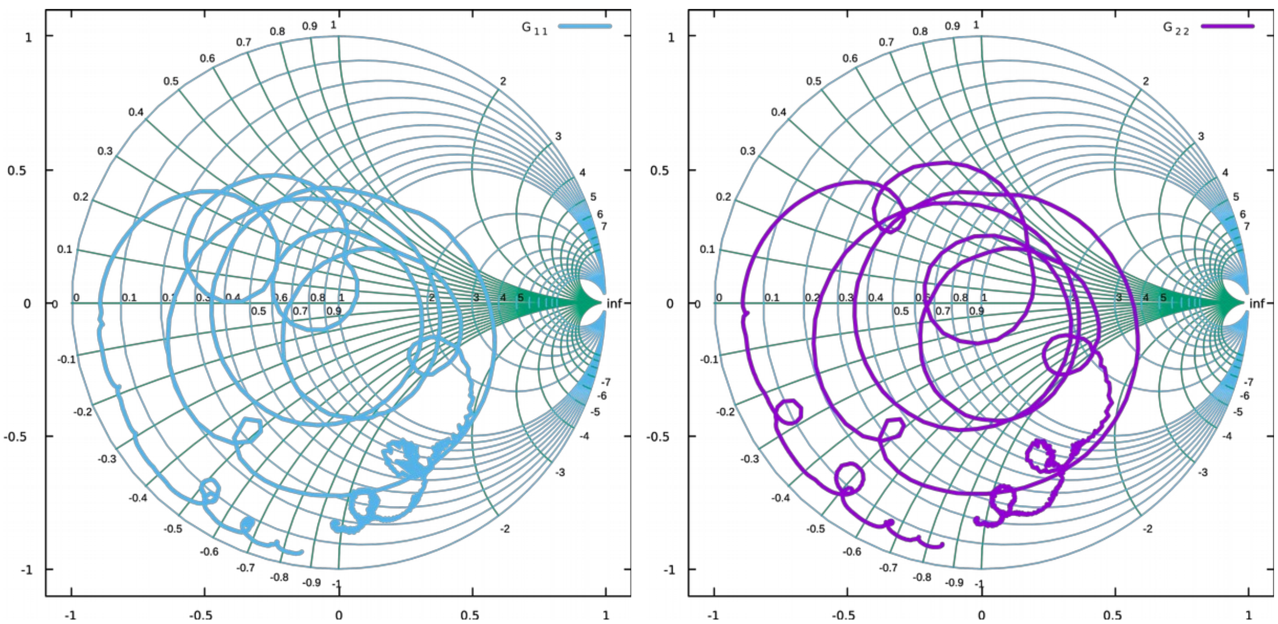


(a) (b)

Fig. 6. Filter (a) Wide band transfer function $|S_{12}|$ (b) Zoom on the close bandpass rejection

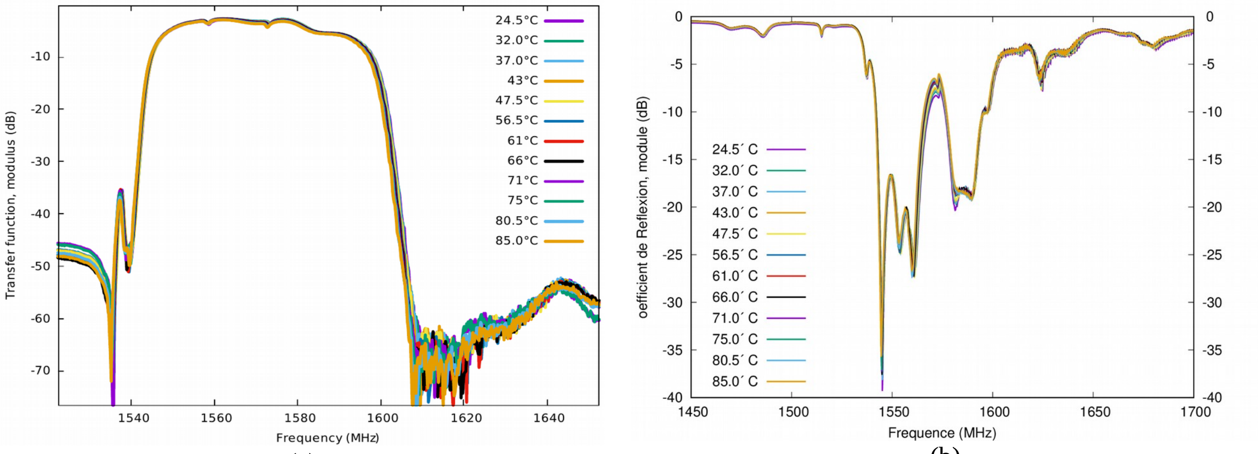


(a) (b)



(c) (d)

Fig. 7. Reflection parameter of the GPS filter derived from S_{11} measurements (a) Reflection coefficient – Input (b) Reflection coefficient – Output (c) Smith Chart – Input (d) Smith Chart – Output



(a) (b)

Fig. 8. Electrical response of the GPS filter built on POI at various temperature – typical temperature stability is better than -10 ppm.K^{-1} corresponding to the upper transition band changes, the band is slightly reducing with temperature (a) Transfer function (b) Reflection coefficient

CONCLUSION

The use of POI wafers combining said thick layers of $LiTaO_3$ (thickness equal to some acoustic wavelength) onto Silicon appear as a very promising solution for high thermal stability high compactness low loss filters for various applications. Absolute temperature stability better than 10 ppm.K^{-1} are currently achieved for filter in L-band with temperature-frequency dependence potentially comparable to Quartz filter thermal characteristics. Considering the temperature compensation principle, there is no effective frequency limitation and probably similar results are achievable in S-band (above 2 GHz). Therefore, very compact and efficient filters are under reach using standard SAW industry techniques contrarily to more complicated solution based on thick Silicon Oxide deposition for instance, requiring more technology steps and a high control of the deposited material quality. Furthermore, the availability of these wafers in 150 mm diameter format yields a very effective industrial solution. Further work is currently achieved to complete the development and provide long term evolution and robustness of the presented filters to aging effects.

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