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OPTIMAL ORIENTATION FUNCTION FOR SAW DEVICES

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Abstract - **The traditional electromechanical coupling coefficient (K^2) and temperature coefficient of delay (TCD); more recently velocity (v_p), for compact or high frequency devices; and now power flow angle (PFA), diffraction (γ), amplitude ($|\Gamma|$) and phase ($\angle\Gamma$) of a metal strip reflection coefficient are equally important in Surface Acoustic Wave (SAW) device design and operation.**

In this paper a novel function which simultaneously analyzes seven SAW propagation properties (v_p, K^2, TCD, PFA, γ, $|\Gamma|$, and $\angle\Gamma$) is discussed and implemented. This flexible function allows the search and selection of optimal propagation directions along arbitrary piezoelectric substrates by employing user defined criteria for each property analyzed which: (i) specify target values; (ii) set acceptable variations from the target values; (iii) assign desired weights; and (iv) normalize to the maximum property value variations for the orientations under study. Given a substrate and a set of basic propagation properties covering a region in the space or in a plane, the function outputs a scalar number for each orientation. The minima indicate optimal orientations with respect to the user defined search criteria and weights.

Contour plots are given showing the function results with respect to orientations in space for different substrates, the historic quartz, and those of more recent interest, the LGX family of crystals. The results validate the usefulness of the optimal orientation function in locating optimal SAW propagation directions and regions in space. Using quartz, for example, attractive propagation properties are confirmed along Euler angles (0°, 43.8°, 23.2°): K^2 is 19% above ST-X, diffraction is minimal, γ and PFA are zero, and the reflection coefficient is almost four times higher than ST-X. Comparisons with previously reported experimental results on quartz and the LGX family of crystals are given.

Keywords **– SAW cuts, SAW devices, new propagation directions, new piezoelectric materials.**

I. INTRODUCTION

The search for optimal surface acoustic wave (SAW) propagation directions in piezoelectric crystals is at the basis of SAW materials and device development. Historically, orientation searches have devoted great attention to looking for high electromechanical coupling coefficient (K^2) and low temperature coefficient of delay (TCD) [1]. Higher K^2 translates into larger possible bandwidth values with reduced insertion loss. Low TCD gives the insensitiveness of the device to temperature variations around a temperature range. Phase velocity (v_p) is another important propagation parameter, which dictates the device's size and maximum allowed frequency given a minimum fabrication dimension for the interdigital transducer (IDT) fingers. Power flow angle (PFA), the angle between the propagation direction of energy with respect to the direction normal to the wavefront, and diffraction (γ), which quantifies the beam spreading, are other historically important parameters considered in the selection of propagation directions in piezoelectric crystals.

The most widely used crystals for SAW applications are: quartz, lithium niobate ($LiNbO_3$), and lithium tantalate ($LiTaO_3$). Other SAW crystals used in the past are: bismuth germanium oxide ($Bi_{12}GeO_{20}$), berlinite ($AlPO_4$), and Gallium Arsenide (GaAs) [1]. Recent materials that have been receiving attention due to the existence of temperature compensated orientations and K^2 larger than quartz, are: lithium tetraborate ($Li_2B_4O_7$); the LGX family of crystal (langasite, LGS; langanite, LGN; and langatate, LGT); and gallium orthophosphate ($GaPO_4$) [2].

Selecting propagation directions in a multitude of piezoelectric crystals based on the several propagation properties previously mentioned may represent a difficult and tedious task. In the past, orientations have been determined based on the simultaneous analysis of contour plots for v_p, K^2, TCD, and PFA [2] [3], and the definition of a three property scalar function for PFA, TCD, and γ, with fixed target values at 0°, 0 ppm/°C, and -1, respectively [4].

The present work presents a flexible scalar function which calculates an optimal substrate orientation in a given material according to a user defined criteria and the propagation properties considered. In addition to v_p, K^2, TCD, PFA, and γ, the function considers the amplitude ($|\Gamma_u|$) and phase ($\angle\Gamma_u$) of an upstep metal strip reflection coefficient [5]. The amplitude and phase of Γ_u is important in SAW device design, especially for resonator structures and natural single phase unidirectional transducer (NSPUDT) orientations, which is the case for promising orientations in the LGX family of crystal [5].

The data regarding the contour plots of the v_p, K^2, TCD, PFA, γ, $|\Gamma_u|$ and $\angle\Gamma_u$ are normalized with respect to the maximum variation found for each property and interpreted under a single scalar function. The user defines desired target values for each property, according to a SAW device design application. In addition, each property can be individually weighted in the function to accommodate the user's importance attributed to each property in the orientation search. Finally the optimum orientation is calculated. A contour plot is generated and used to display the resulting function and identify the optimal orientation based on the user defined target values and weights for each property. The function is very flexible in the sense that the

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idea can be easily extended to incorporate other propagation properties in the future, if necessary.

This paper contains four sections. Section II describes the implementation of the optimal orientation function and the respective input data. Section III presents numerical and experimental verification of the function based on quartz and langatate orientation results. The final section is devoted to conclusions.

II. Function implementation

A. Inputs

The optimization function is dependent upon previously calculated contour plot data for each of the seven properties under consideration, namely v_p, K^2, TCD, PFA, γ, $|\Gamma_u|$, and $\angle\Gamma_u$ [2], [3], [5], and three user defined inputs which set the calculation parameters for each property. The three required inputs are:

- The target value for each property (T_{prop});
- The allowed range around each property target value (R_{prop});
- The weight for each property (W_{prop})

where the subscript *prop* stands for "*property*" and refers to each individual property.

The target property value, T_{prop}, is used to define the desired value for each SAW propagation property considered. For example, one can select the desired target values for {v_p, K^2, TCD, PFA, γ, $|\Gamma_u|$, $\angle\Gamma_u$} to {min [km/s], max [%],0 [ppm/°C],0 [°],-1,max,180 [°]}. *Min* and *max* stand for *minimum* and *maximum* and can be replaced by a specific numerical value. The target values can be adjusted according to different applications. For instance, one might be interested in finding the minimum v_p for diminishing the dimension of a particular SAW device, or in the maximum v_p in order to design high frequency SAW devices and diminish the requirements on the minimum photolithographic dimensions.

The allowed range around each property target value, R_{prop}, is used to filter out orientations that have one or more propagation properties with values that that are of no interest or even unacceptable for a particular SAW application. For instance, orientations with extremely low electromechanical coupling, or relatively high TCD may be avoided from the beginning, even if other property values are very close to the target.

The weight for each property, W_{prop}, allows the user to define the importance given to each property considered, and assumes values between zero and one. For instance, one might be looking for high K^2, low TCD, and high $|\Gamma_u|$, and might not be too much concerned about PFA, v_p, γ, and $\angle\Gamma_u$. In this case a weighting vector for {v_p, K^2, TCD, PFA, γ, $|\Gamma_u|$, $\angle\Gamma_u$} could be, for instance, {0, 1, 0.8, 0, 0, 1, 0}. Weighting each property individually gives the user great flexibility and control to search for the optimal orientation for a specific application. Table I summarizes the input variables and respective range.

TABLE I
OPTIMIZATION FUNCTION INPUTS REQUIRED

INPUT	VALUE	USAGE
Target (T_{prop})	Desired value for each property	Defines the target property value to achieve for each property.
Range (R_{prop})	Allowed variation from T_{prop}	Used to flag orientations that are of no interest, due to one or more propagation properties falling outside the allowed user defined range.
Weight (W_{prop})	$0 \leq W_{prop} \leq 1$	Defines the weight of each property in the optimization calculation. A weight of 0 is not considered, and a weight of 1 has maximum consideration.

B. Target Comparison

The first step in implementing the function is to calculate the difference between the defined target value, T_{prop}, and the respective calculated property value, dat_n, for each property at each orientation.

$$|T_{prop} - dat_n| = Variation_n \tag{1}$$

where $n = 1, 2, 3,\ldots, m$, and m is the number of orientations considered by the function. If $Variation_n$ is zero, the target value is satisfied at the given orientation. The absolute value is taken to avoid carrying an arbitrary sign with the variable $Variation_n$, which would prevent the straightforward addition of discrepancies of different properties in the scalar function.

When a calculated $Variation_n$ is outside of the allowed range, R_{prop}, a flag is set to show the user that the particular orientation is of no interest or even unacceptable for a particular SAW application. In this case, $Variation_n > R_{prop}$.

C. Normalization

Once $Variation_n$ is calculated for all m orientations, a search is performed to find the greatest $Variation_n$ for each property, named $MaxVar_{prop}$. The respective data set regarding all the m orientations under consideration for each property is then divided by its $MaxVar_{prop}$. The new data set generated for each property is named *Normalized Data*$_n$, as indicated by

$$\frac{Variation_n}{MaxVar_{prop}} = Normalized\ Data_n \tag{2}$$

Therefore, for each property the orientation (or orientations) with calculated property value furthest from the respective target value are assigned one, whereas calculated property values that are equal to the respective target value receive zero. All of the other *Normalized Data*$_n$ are between 0 and 1 for each property ($0 \leq Normalized\ Data_n \leq 1$).

This normalization technique is dependent upon the data set under consideration. The normalized data for each property is relative to the property response for a given substrate and range of orientations selected. The normalization operation guarantees that the *Normalized* $Data_n$ for all properties lie between zero and one.

D. Property Weighting

Weights, W_{prop}, are scalars assigned by the user to each property in the function. These input variables are introduced to allow the user to quantify the importance of meeting each property target in the orientation search for a specific SAW application. The user assigns weights ranging from 0 to 1 to each property. A weight of zero means that the property is irrelevant in the function, and therefore in the orientation search. A weight of one considers the property to be of maximum importance.

The product of W_{prop} and *Normalized* $Data_n$ is the normalized and weighted property value that is used in the optimization function for each orientation and each property under consideration, $Opt_{n,prop}$.

$$W_{prop} \times Normalized\ Data_n = Opt_{prop,n} \tag{3}$$

E. Optimization Function Evaluation and Interpretation

The final step is to combine all the properties considered at each individual orientation. The target variation calculation, normalization, and weighting previously described generated the $Opt_{n,prop}$ set of data for each property and at each orientation. Since we are considering seven properties, v_p, K^2, TCD, PFA, γ, $|\Gamma_u|$, and $\angle\Gamma_u$, the function result collects all of the seven normalized and weighted property values for each orientation in a single summation.

$$Opt_n = \sum_{prop} \left(Opt_{prop,n} \right) \tag{4a}$$

or

$$Opt_n = Opt_{vp,n} + Opt_{K^2,n} + Opt_{TCD,n} + + Opt_{PFA,n} + Opt_{\gamma,n} + Opt_{|\Gamma|,n} + Opt_{\angle\Gamma,n} \tag{4b}$$

The optimal orientation function result is a scalar value ranging from 0 to 7 for each orientation. Zero represents the most optimal orientation, where all the target values considered have been achieved, and seven represents the worst orientation for the target values selected. Generally speaking one is thus looking for the minimum or minima which results from (4), which represent the best orientations with respect to the selected targets for the propagation properties considered. Contour plots are used to visualize the relatively low scalar values of the optimal orientation function, which represent the optimal orientations searched.

The following section gives typical examples of the optimization function for both quartz and LGT.

III. Numerical and Experimental Verification

A. Quartz Propagation Properties

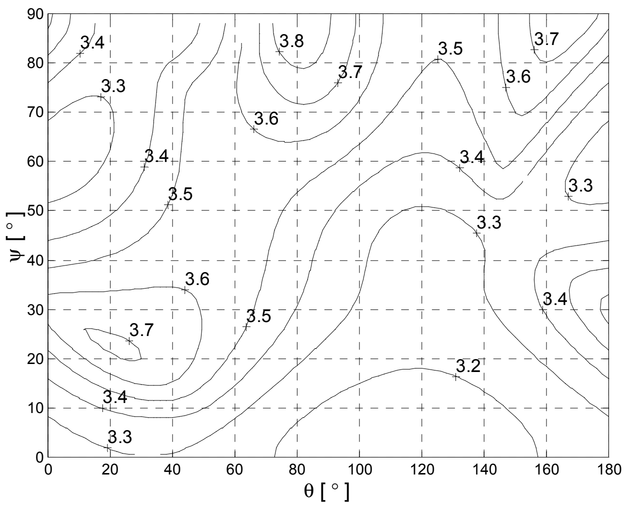
Quartz Euler angles (ϕ, θ, ψ) = (0°, θ, ψ) has been selected as the first material to exemplify the use of the optimal scalar function created. The crystal is well established and its SAW propagation properties contour data for v_p, K^2, TCD, PFA, γ, $|\Gamma_u|$, and $\angle\Gamma_u$ were calculated using the material constants from [6]. Fig. 1 shows contour plots for v_p, K^2, TCD, PFA, and γ. Fig. 2 shows upstep metal strip reflection coefficient magnitude, $|\Gamma_u|$, and phase, $\angle\Gamma_u$, contour plots for aluminum strips of h/λ=1%, where h is the thickness of the metal strip and λ is the wavelength.

The phase velocity values, shown in Fig. 1a, range from about 3.2 km/s to 3.8 km/s for the selected quartz orientations. Fig.1b shows that K^2 has reduced values for ψ above about 50°, which is of little interest in SAW device applications. High K^2 for quartz is found for θ between 30° to θ=150° and ψ between 0° and 30°. Fig.1c shows the TCD contour plot calculated around 25° C. Zero TCD can be observed around several regions of the contour plot, although some have quite reduced coupling. Fig 1d depicts the calculated PFA, and shows the existence of several locations where null PFA can be found. Fig. 1e plots γ, calculated as the derivative of the PFA with respect to the third Euler angle. The minimal diffraction is given by [1]

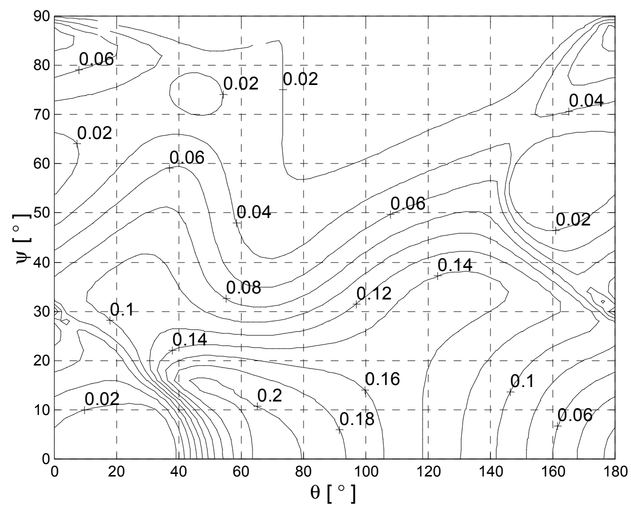
$$\gamma = \frac{d(PFA)}{d\psi} = -1 \tag{5}$$

The best propagation direction for the quartz orientations under consideration depend on how many of the one to seven properties are being considered, and the relative weights assigned to each property. Regions of interest for quartz include those of zero TCD and PFA, maximum K^2 possible, and diffraction as close to -1 as possible. On each of the contour plots shown, there are several regions where the SAW propagation properties individually meet the respective target values mentioned.

A qualitative analysis of the plots shown in Fig. 1 shows that the individual properties are close to the target values mentioned for θ between 20° and 60° and ψ between 10° and 30°, depending on the relative weights assigned to each individual property. However, it is difficult to distinguish and establish where all property targets are best jointly met. Determining the optimal orientation based on the comparison of the several property contour plots is a tedious, complicated, and imprecise task. Using the optimization function, all seven of the properties shown are normalized and mathematically evaluated to produce the most desired orientations given a set of user defined inputs.



(a)



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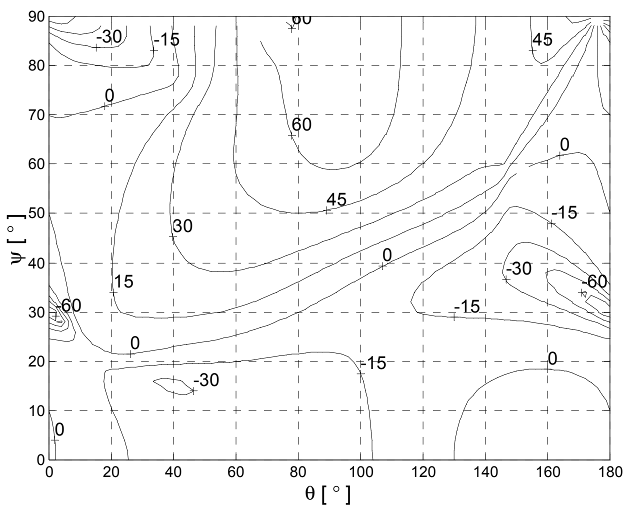

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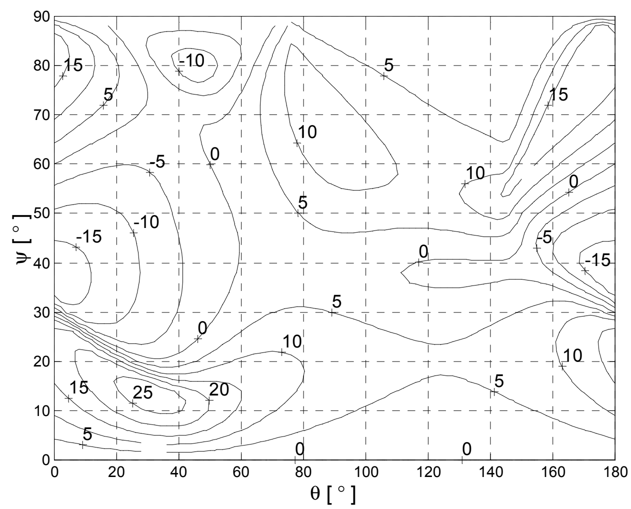
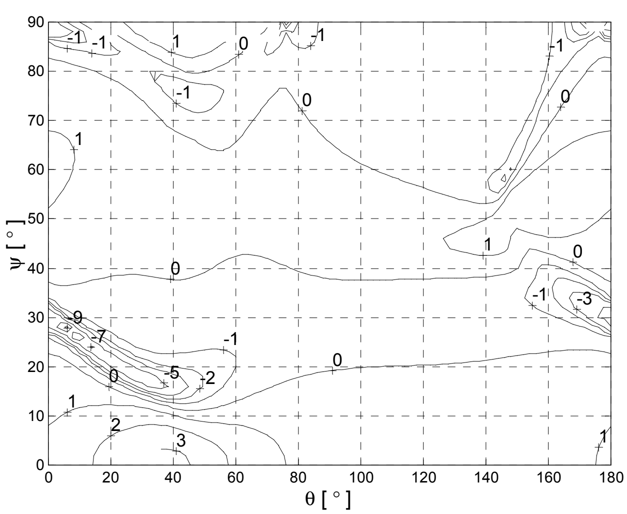


(d)



(e)

Fig. 1. Contour Plots for SAW Quartz Euler angles (ϕ, θ, ψ) = (0°, θ, ψ): (a) v_p [km/s]; (b) K^2 [%]; (c) TCD [ppm/°C]; (d) PFA [°]; (e) γ. (a), (c), (d), and (e): free surface.

Next the optimal orientation function is used as a tool in finding the most desired region for a particular SAW substrate response given the properties under consideration.

B. *Optimal Orientations for Quartz (0°, θ, ψ)*

Table II shows the target values considered in this quartz Euler angles (0°, θ, ψ) example. The influences of v_p, $|\Gamma_u|$, and $\angle\Gamma_u$ are not considered. The target values for {K^2, TCD, PFA, γ} are {max, 0ppm/°C, 0°, -1}. Two cases will be studied based on different weights assigned to the properties considered. In the first case K^2, PFA, TCD, and γ are all given equal weights of one, and the remaining properties are weighted with zero. In the second case, only K^2, PFA, and TCD are considered in the function (γ also receives zero weighting).

The resultant contour plots for these function inputs are shown in Fig. 3a and 3b. Function minima are observed around Euler angles (0°, 44°, 23°) for both plots. Considering diffraction, the optimal orientation function

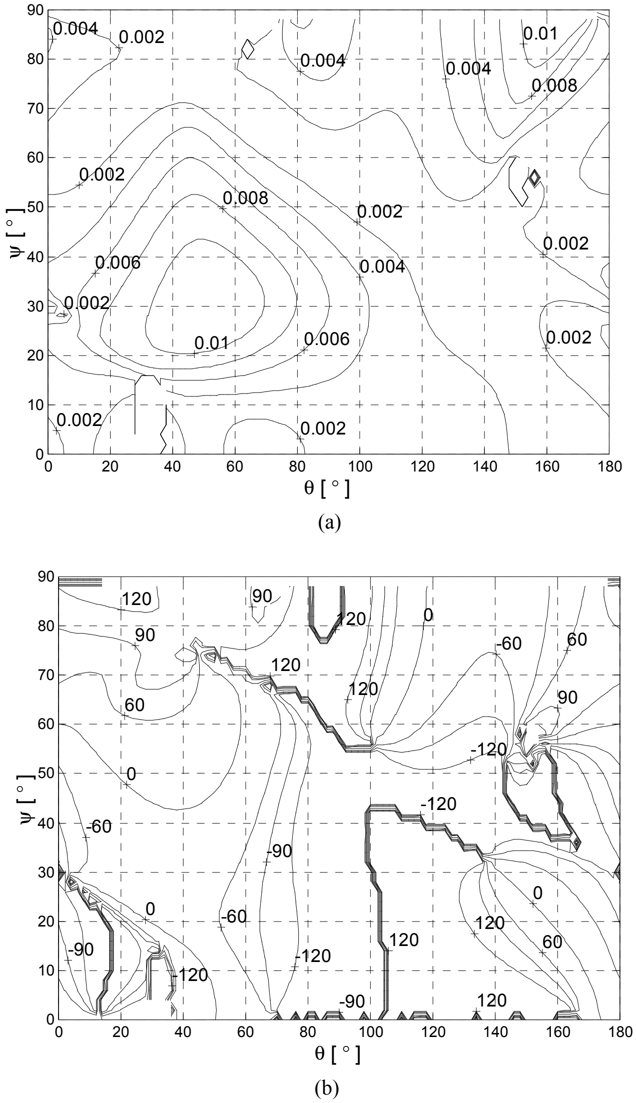


Fig. 2. Contour Plots for SAW Quartz Euler angles (ϕ, θ, ψ) = (0°, θ, ψ): upstep strip reflectivity (a) $|\Gamma_u|$, and (b) $\angle\Gamma_u$.

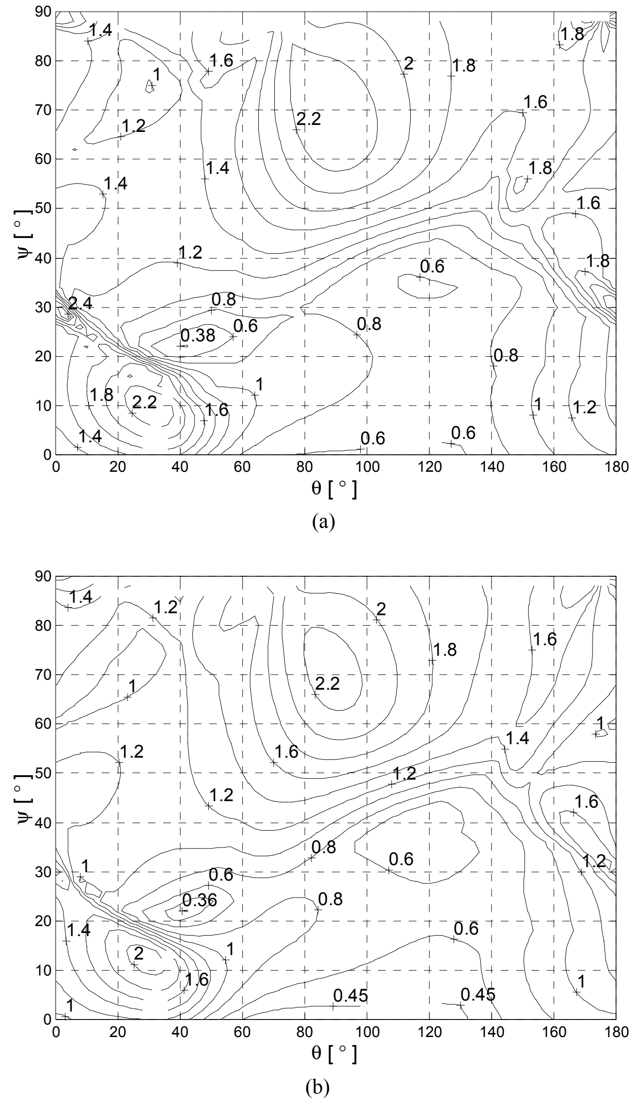


Fig. 3. Contour Plots for SAW Quartz Optimization Euler angles (ϕ, θ, ψ) = (0°, θ, ψ): (a) considering K^2=Max, TCD=0, PFA=0, γ=–1; (b) considering K^2=Max, TCD=0, PFA=0.

TABLE II
OPTIMIZATION FUNCTION INPUTS FOR QUARTZ ANALYSIS

PROPERTY		Target	Weight	
			Fig. 3 (a)	Fig 3 (b)
V_p	(km/s)	---	0	0
K^2	(%)	Max	1	1
TCD	(ppm/°C)	0	1	1
PFA	(°)	0	1	1
γ		-1	1	0
|Γ|		---	0	0
∠Γ	(°)	---	0	0

TABLE III
OPTIMIZATION FUNCTION PROPERTY RESULTS

PROPERTY		Target	ST-X	(0°,43.8°,23.2°)
V_p	(km/s)	---	3.16	3.63
K^2	(%)	Max	0.12	0.14
TCD	(ppm/°C)	0	1.32	-0.19
PFA	(°)	0	0.00	0.00
γ		-1	0.38	-0.91
|Γ|		---	0.003	0.011
∠Γ	(°)	---	-180.0	-46.2

indicates a minimum of value 0.38 at Euler angles (0°, 43.8°, 23.2°). The same orientation is obtained if diffraction is neglected, with a function value of 0.36, which clearly indicates that the orientation is optimal for all four properties considered. For comparison, the optimal orientation function values for ST-X quartz Euler angles (0°, 132.75°, 0°) changes from 0.45 to 0.6 when the diffraction is considered, as can be verified from Fig. 3. This is because the diffraction effect is significant for ST-X quartz with respect to the (0°, 43.8°, 23.2°), as previously seen in Fig. 1e. Note that the (0°, 43.8°, 23.2°) orientation performance is superior with respect to ST-X even when diffraction is not included in the analysis. Table III shows the resultant property values for both ST-X and (0°, 43.8°, 23.2°) orientations.

This optimal quartz orientation vicinity has been identified, discussed, and experimentally tested in [4], where the authors arrived at Euler angles (0°, 43°, 23.7°) by considering in their analysis TCD, γ, and PFA. The experimental results reported in [4] show measured diffraction of –0.97, zero TCD, 0.135% for K^2, and zero PFA, which is consistent with the predicted in this work.

It is interesting to mention that $\angle\Gamma_u$ is –46.2° which denotes some degree of directivity in the (0°, 43.8°, 23.2°) orientation. It should also be noted that the K^2 for the optimal orientation is 17% higher than that of ST-X, and the calculated diffraction is -0.91 compared to 0.38 for ST-X.

The optimization plots also show several areas to avoid. In both function outputs, there are no relatively low scalar values above $\psi = 40°$. This is expected, since the K^2 target value is not approached in this region.

It is important to note that the optimization function results must be interpreted in a relative manner. The poor orientations have function outputs relatively high with respect to the optimal orientation. For instance, Fig. 3 shows values of 2.2 in some locations, which are more than 6 and 5.7 times higher than the minimum location values of 0.36 and 0.38, respectively.

C. Optimal Orientations for Langatate (0°, θ, ψ)

Fig. 4 shows the calculated LGT contour plots for γ, $|\Gamma_u|$, and $\angle\Gamma_u$. The contour plots for v_p, K^2, TCD, and PFA have been given in [3], together with the LGT material constants and temperature coefficients used. In [3] the contour plot analysis based on v_p, K^2, TCD, and PFA suggested optimal LGT orientations at (0°, 151.2°, 24°) and (0°, 143.9°, 23.9°) for high K^2, zero TCD, and zero PFA.

Using the function presented in this work, the property targets for {K^2, TCD, PFA, γ, $|\Gamma_u|$, $\angle\Gamma_u$} have been set to {max [%],0 [ppm/°C],0 [°],-1,max, 90 [°]}, as shown in Table IV. Note that v_p has not been considered in the analysis, since it has zero weight for all the three cases considered, each with a different set of weight. Case 1 considers all properties, but phase velocity, in the analysis; Case 2 does not consider γ; and Case 3 does not consider TCD; as can verified by the respective zero weights in Table IV. The weight assigned to K^2 is 0.5, and the weights assigned to $|\Gamma_u|$ and $\angle\Gamma_u$ are 0.25. Since the most interesting LGT region also presents directivity, one might as well try to optimize the magnitude and phase of the strip reflection coefficient [7] for natural single phase unidirectional transducers (NSPUDT) applications.

Fig. 5 shows the contour plot for Case 1. The optimal function outputs scalars which vary from 0.62 at the minimum to 2.60 at the areas of greatest variation from the jointly considered targets. Fig. 5 indicates that the region around Euler angles (0°, 140°, 26°) indeed has the most promising orientations. Table V indicates the best orientations for the three cases considered. For Case 1, the orientation (0°, 144.1°, 23.9°) represents the better compromise, and the Euler angles are very similar to the one of the orientations mentioned in [3]. Note that for this orientation, γ is relatively away from the –1 target value, and that diffraction has not been considered in [3]. Case 2,

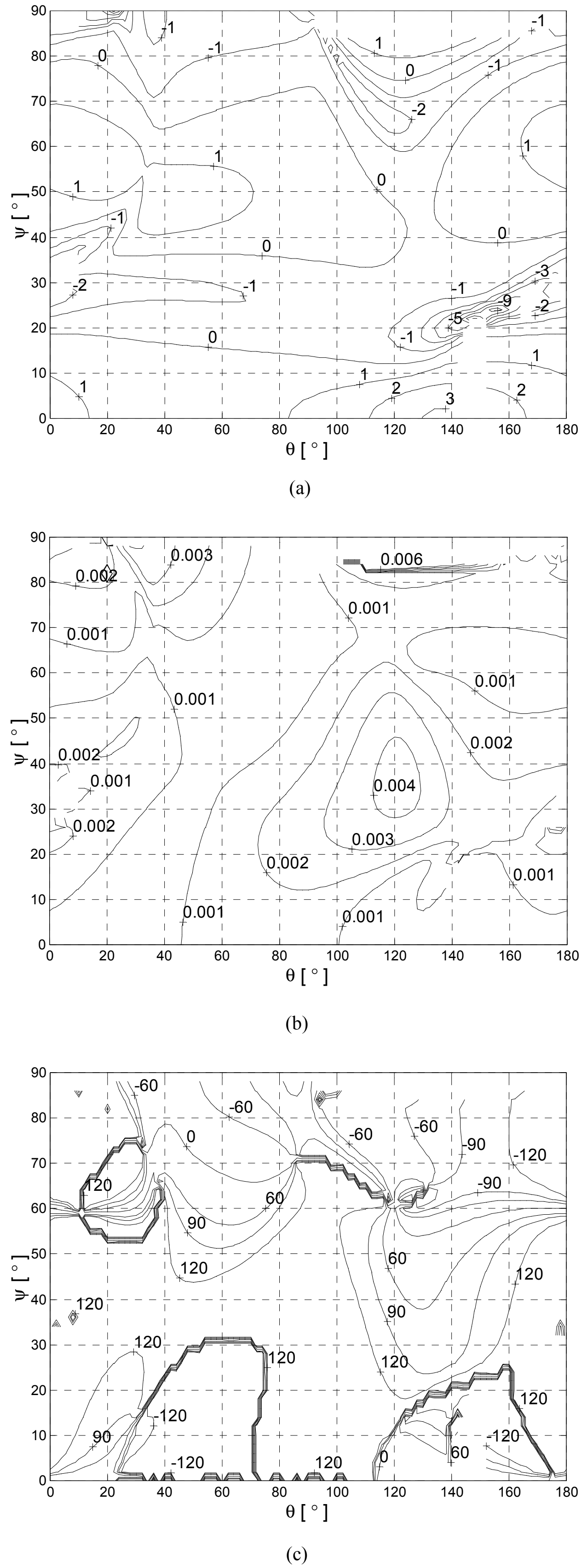


Fig. 4. Contour Plots for SAW Langatate Euler angles (ϕ, θ, ψ) = (0°, θ, ψ): (a) γ; upstep strip reflectivity (b) $|\Gamma_u|$ and (c) $\angle\Gamma_u$..

TABLE IV
OPTIMIZATION FUNCTION INPUTS FOR LGT ANALYSIS

PROPERTY		Target	Weight		
			Case 1	Case 2	Case 3
V_p	(km/s)	---	0	0	0
K^2	(%)	Max	0.5	0.5	0.5
TCD	(ppm/°C)	0	1	1	0
PFA	(°)	0	1	1	1
γ		-1	1	0	1
$\lvert\Gamma\rvert$		Max	0.25	0.25	0.25
$\angle\Gamma$	(°)	90°	0.25	0.25	0.25

TABLE V
OPTIMIZATION FUNCTION RESULTS FOR SPECIFIED CASES

PROPERTY		Case 1	Case 2	Case 3
		(0,144.1,23.9)	(0,151.2,24)	(0,138.4,26.3)
V_p	(km/s)	2.61	2.62	2.59
K^2	(%)	0.59	0.71	0.43
TCD	(ppm/°C)	0.09	-0.02	-5.60
PFA	(°)	0.02	0.04	-0.04
γ		-2.42	-5.89	-1.00
$\lvert\Gamma\rvert$		0.0021	0.0021	0.0027
$\angle\Gamma$	(°)	117.57	154.41	83.56

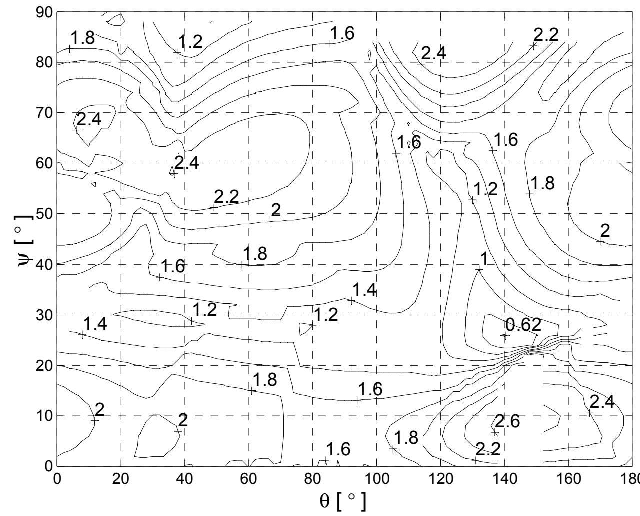


Fig. 5. Contour Plots for SAW LGT Optimization Euler angles (ϕ, θ, ψ) = (0°, θ, ψ): (a) considering K^2=Max, TCD=0, PFA=0, γ=–1, $\lvert\Gamma\rvert$=Max, and $\angle\Gamma$=90°. Using Case 1.

which assigns zero weight to γ, gives (0°, 151.2°, 24°) as the best orientation, in agreement with [3]. Case 3, which assigns zero weight to TCD, gives (0°, 138.4°, 26.3°) as the best orientation, with γ=-1 and TCD=-5.6 ppm/°C. K^2 is high for the three regions mentioned, but higher for Case 2, the worst case for γ. Therefore, it can be seen that given a specific substrate application, propagation property weights can be adjusted to search for optimal orientations.

IV. Conclusion

A scalar optimal orientation function has been presented which allow for easy search and determination of optimal SAW orientations based on propagation properties contour plot data.

Seven SAW propagation properties have been considered in this work: {v_p, K^2, TCD, PFA, γ, $\lvert\Gamma_u\rvert$, $\angle\Gamma_u$}. The optimal function assigns user defined target values and weights for each property and allows the user to search and find optimal orientations based on a specific application.

The optimal function has been implemented and applied to quartz and LGT Euler angles (0°, θ, ψ) examples. The results are compared to previously calculated and experimental results, showing the usefulness and ease of use of the optimal orientation function in searching and define the better orientation for a specific SAW application.

Acknowledgment

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References

[1] D. P. Morgan, *Surface-Wave Devices for Signal Processing*, Amsterdam, Netherlands, Elsevier Science Publishers B. V., 1985.

[2] M. Pereira da Cunha and S. A. Fagundes, "Investigation on Recent Quartz-like Materials for SAW Applications," *IEEE Trans. Ultrason. Ferroelec. Freq. Contr.*, Vol. 46, No. 6, November 1999, pp. 1583-1590.

[3] M. Pereira da Cunha, D.C. Malocha, E.L. Adler, K.J. Casey, "Surface and Pseudo Surface Acoustic Waves in Langatate: Predictions and Measurements," *IEEE Trans. Ultrason. Ferroelec. Freq. Contr.*, Vol. 49, No. 9, September 2002, pp. 1291-1299.

[4] B. P. Abbott and L. P. Solie, "A minimal diffraction cut of Quartz for high performance SAW filters," in *Proc IEEE Ultrasonics Symposium*, 2000, pp. 235-240.

[5] M. Pereira da Cunha and S. de A. Fagundes, "Metal Strip Reflectivity and NSPUDT Orientations in Langanite, Langasite, and Gallium Phosphate," *IEEE Trans. Ultrason. Ferroelec. Freq. Contr.*, Vol. 49, No. 6, June 2002, pp. 815-819.

[6] R. Bechmann, A. D. Ballato, and T.J. Lukaszek, "Higer-Order Temperature Coefficients of the Elastic Stiffnesses and Compliances of Alpha-Quartz" in *Proc. of the IRE*, Vol. 50, Aug. 1962, pp. 1812-1822.

[7] M. Pereira da Cunha and E. L. Adler, "A Network Model for Arbitrarily Oriented IDT Structures," *IEEE Trans. Ultrason. Ferroelec. Freq. Contr.*, Vol. 40, No. 6, November 1993, pp. 622-629.