

Optimization design of electrode configurations of lithium niobate tuning fork sensor

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Abstract Due to its distinctive dual-cantilever structure and vibrational mode, the tuning fork (TF) sensor can simultaneously and decoupledly measure fluid density and viscosity. This has led to its extensive application in various industrial sectors, such as oil and gas exploration, petrochemical processing, food production, and textiles. The magnitude of the quality factor (Q) is restricted by the effective electromechanical coupling coefficient. A higher coupling efficiency indicates more efficient energy conversion between electrical and mechanical domains, thus improving the Q value. This efficiency is influenced by multiple factors, including the design of the electrode configuration, layout, material properties, and geometric configuration. This study optimizes lithium niobate TF (LNTF) electrode configurations by integrating piezoelectric equations, thermoelastic effects, and contact models into an analysis framework to quantify electromechanical coupling, temperature coefficient of frequency (TCF), and Q value across configurations, with air experiments validating multiple mounting methods. The simulation results show that the double-sided electrode configuration 2 (a pair of positive and negative electrodes is patterned on one surface of each tuning fork arm, and the same electrode arrangement is symmetrically implemented on both the upper and lower surfaces) exhibits the highest excitation efficiency. Within 20–180 °C, the single-sided + suspended electrode configuration shows the smallest TCF (−73.01 ppm/°C) and better stability. Under elevated temperatures, double-sided electrode configuration 2 exhibits minimal Q value drift (6.06%), superior thermal stability, and suitability for fluid parameter measurement, supported by experimental validation of simulation findings. A comparative analysis of vibration characteristics under various electrode mounting methods in air and several standard oils verifies that the double-sided electrode configuration 2 exhibits excellent comprehensive performance, making it highly suitable for fluid sensor applications. This research provides theoretical bases and experimental evidence for the optimized electrode design of LNTF sensors.

Keywords Lithium niobate tuning fork, Electrode configuration, Effective electromechanical, Fluid measurement

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1 Introduction

As key physical properties of fluid characteristics, density and viscosity hold extensive and indispensable importance in industrial production. The measurement outcomes are directly related to process stability, product quality control, and equipment operational safety. Specifically, real-time monitoring in complex operational environments has emerged as a crucial component in the technological advancement across various industries. For instance, in the production or synthesis of diverse chemical products, the dynamic variations in density and

viscosity under high temperature and pressure directly indicate the chemical reaction process (e.g., molecular weight distribution and molecular chain growth rate) and phase transitions, which subsequently influence the quality of the chemical products. Density and viscosity measurements are extensively employed in transformer oil quality assessment^[1], space shuttle engine vibration monitoring^[2], wine brewing oversight, and biological concentration detection^[3] within the biomanufacturing sector.

Owing to its specific double cantilever beam structure and vibration mode, the tuning fork (TF) sensor could

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achieve synchronous decoupling measurement of fluid density and viscosity. Firstly, the TF sensor has simple equipment and low cost, and is easy to realize in the process^[4,5]. Secondly, the TF sensor system features simple equipment, involves minimal cost, and facilitates straightforward process realization.

Lithium niobate (LN) features a high electromechanical coupling coefficient and exhibits outstanding resistance to temperature and pressure, making it a high-demand material for piezoelectric transducers and sensors in recent years^[6]. Fork sensors fabricated from LN have also demonstrated rapid development. Cantatore *et al.*^[7] utilized an LNTF sensor as a photoacoustic spectroscopic gas sensor with a single-sided electrode. The measuring signal remained steady at a noise level of 2 ppm. Meanwhile, owing to its resistance to high temperatures and pressures, it is anticipated to represent a novel avenue for the advancement of downhole fluid sensors. The selection of the electric field and electrode design is crucial in the design process of downhole high-temperature LNTF sensors to enhance their performance. Consequently, research on this issue is imperative. In 2012, Toda *et al.*^[8] introduced an LNTF comprised of two 0.5 mm LN wafers, including a U-shaped electrode centrally positioned and an inverted electrode configuration. The inverted electrode configuration increased the tip amplitude and overall sensitivity double. In 2017, Gonzalez *et al.*^[9] utilized the LNTF (dimensions: 8 mm × 1 mm × 1 mm) supplied by TC Company as a TF sensor for the rapid detection of fluid density and viscosity in the well, without addressing the optimization of the electrode configuration. Ahlstrom *et al.*^[10] designed a solid sensor utilizing LNTF as the primary sensing element, and detected solid helium (⁴He) under conditions nearing the melting pressure using an internal nested electrode in conjunction with a portion of a suspended electrode. In 2011, Liu *et al.*^[11] designed an LNTF sensor that contains positive and negative electrodes positioned centrally, enabling the measurement of density and viscosity of fluids at high temperature and pressure conditions. The measured results corresponded well with the literature values. Turutin *et al.*^[12] developed a double-domain sensor with an LN and metallic glass layer through a patch electrode design, which efficiently mitigated thermal noise in alternating current magnetic field measurements. While current research on LNTF sensors addresses material property optimization, packaging process enhancement, and low-frequency signal processing, there is a lack of study concerning the interaction mechanism between electrode configurations and mechanical coupling efficiency.

This paper focuses on the electrode design of an LNTF utilizing an LN (LiNbO₃) single crystal cut by 128° *Y-X*. The effective piezoelectric coefficient d_{23} of 128° *Y-X*-cut LiNbO₃ is approximately ten times of the d_{11} (2–3 pC/N) of α -quartz crystal, which is the sole piezoelectric coefficient influencing the excitation of the first-order in-plane bending vibration. Moreover, its density and Young's modulus

are 4650 kg/m³ and 145 GPa, respectively, surpassing the values of 2660 kg/m³ and 72 GPa for α -quartz^[7]. In this paper, the electromechanical response characteristics of LNTF sensors in the first-order in-plane bending mode by the finite element numerical simulation method were systematically analyzed. The influence mechanisms of six electrode configurations, e.g., single-sided, single-sided + suspended, embedded, embedded + suspended, double-electrode 1, and double-electrode 2, on admittance characteristics, resonant parameters, and high-temperature stability were analyzed. By quantitatively assessing the variations in effective electromechanical coupling coefficients (k_{eff}^2), temperature coefficients of frequency (TCF)^[13], and quality factors (*Q*-factors) among configurations, corresponding LNTF sensor samples were produced and experimentally validated for performance comparison. This study provides theoretical and technical assistance for the advancement of high-performance LNTF sensors.

2 Theoretical foundation

The LNTF can be considered as a cantilever beam, fixed at one end and free at the other, due to its length being substantially greater than its width and thickness. When it oscillates with minimal amplitudes in a fluid, it is primarily influenced by a harmonic driving force and a drag force that is linearly correlated to its velocity, as described by the subsequent equation^[14]:

$$\frac{d^2x}{dt^2} + \gamma \frac{dx}{dt} + \frac{k}{m}x = \frac{F}{m}, \quad (1)$$

where m refers to the effective mass of the cantilever beam, which mainly influences its resonant frequency; γ represents the damping coefficient, which primarily affects the quality factor; k denotes the elastic stiffness parameter of the single cantilever; F is the external force excitation: $F = F_0 e^{-i\omega t}$, and F_0 indicates the amplitude of the force. The effective mass and damping coefficient are significantly influenced by the characteristics of the fluid.

The representation of m_{eff} is

$$m_{\text{eff}} = \frac{\rho L T W}{4}, \quad (2)$$

where ρ is the density of the piezoelectric material, while L , T , and W represent the length, thickness, and breadth of the cantilever beam, respectively.

The TF is triggered by an alternating current of $V = V_0 e^{-i\omega t}$, and the driving force of each cantilever beam is

$$F = \frac{aV}{2}, \quad (3)$$

where a represents the fork-finger constant, V is the voltage necessary to induce the LNTF vibration, V_0 denotes the voltage amplitude, and the current generated is directly

proportional to the velocity of the fork-finger tip:

$$I = av, \quad (4)$$

where the fork-finger constant a is^[10]

$$a = \sqrt{\frac{4\pi\omega_{\text{eff}}\Delta f_2 I_0}{V_0}}, \quad (5)$$

where Δf_2 , I_0 , and ω_{eff} represent the bandwidth of the resonance, the current amplitude at the resonance frequency, and the resonance frequency of the cantilever beam in a vacuum, respectively. a is an important parameter that connects the electrical and mechanical characteristics of resonant devices. When the system reaches the resonant frequency, the amplitude attains its maximum value, denoted as x_{max} . An analysis of the equation reveals that

$$x_{\text{max}} = \frac{F_0}{m_{\text{eff}}\gamma\omega_0^2} = \frac{aV_0}{2\gamma\omega_0^2}, \quad (6)$$

where ω_0 is the frequency at which the tuning fork vibrates in the actual working environment.

Y_e is the measured electrical admittance, which generally includes two parts: the real part and the imaginary part. The definition is

$$Y_e = \frac{I}{V}. \quad (7)$$

By substituting Eqs. (4), (5), and (7) into Eq. (6), we can derive

$$x_{\text{max}} = \frac{V_0}{2\omega_0} \sqrt{2Y_{e,\text{max}}}. \quad (8)$$

As can be seen from Eq. (8), when given the same excitation, the larger the amplitude, the greater the value of conductance. This leads to a higher signal-to-noise ratio (SNR) during measurement, facilitating the accurate extraction of resonant frequency and quality factor.

By acquiring the current of the TF sensor at a specific driving voltage, it is possible to calculate the vibration velocity at the fork-finger tips of the TF in fluid, thus allowing the calculation of other parameters. Therefore, it is necessary to thoroughly examine the intrinsic relationships among the excitation efficiency of various electrode configurations, the vibration velocity at the fork-finger tips, the quality factor, and other parameters to inform the optimization of electrode design.

It is essential to choose structural dimensions that are responsive to fluctuations in fluid properties when using a TF sensor to measure the characteristic properties of high-temperature and high-pressure fluids. Figure 1 shows the structure of the LNTF that was optimized previously to this work. Its dimensions are 8 mm in arm length, 1 mm in width, and 1 mm in thickness^[15].

The optimization of the structural dimensions of the TF sensor has been proposed in previous studies^[15]. In this paper, the optimized structural dimensions are used during

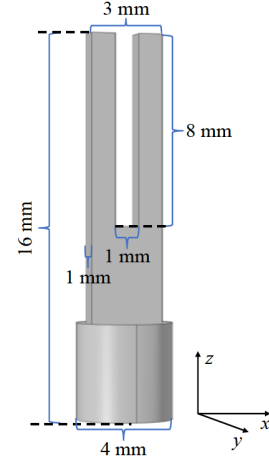


Fig. 1 3D schematic diagram of LNTF.

simulation. The cylindrical shape is its base, and the length of the LNTF is 8 mm, and the width and thickness are both 1 mm.

The finite element simulation is conducted utilizing the solid mechanics and electrostatic modules of COMSOL to calculate the resonant frequency, admittance curve, and fork-finger tip displacement of the TF during vibration in a vacuum^[7,16]. In the three-dimensional (3D) simulation, the geometry was meshed with free tetrahedral elements, with the mesh size kept below 1/5 of the elastic wavelength to capture the wave propagation accurately. A fixed support was imposed on the base of the cylindrical pedestal, leaving all other boundaries free.

$$E = -\nabla V, \quad (9)$$

$$\nabla \cdot D = \rho_v, \quad (10)$$

$$D = \varepsilon_0 \varepsilon_{\text{LN}} E + P_{\text{pze}}, \quad (11)$$

where E , V , and D are the electric field, the electric potential, and the Maxwell displacement field, respectively, generated via the piezoelectric effect within the LNTF; ρ_v is the volume density of piezoelectric charge; LiNbO_3 is the 128° Y - X -cut LiNbO_3 relative permittivity tensor; and P_{pze} is the piezoelectric polarization density field.

3 Optimal electric field orientation

In the electrode design process of an LNTF, adjusting the direction of the electric field or the configuration pattern of the electric field is a crucial stage to ensure optimal performance.

This paper selects a commonly manufactured 128° Y - X -cut LN wafer for the purpose of design. While various cut angles exist, the 128° Y - X -cut was chosen for its optimal balance between performance and practicality. Specifically, it exhibits a relatively high k_{eff}^2 , which facilitates signal

generation and sensitivity for viscosity sensing. As the standard substrate for SAW filters, it guarantees exceptional material consistency and stability, which is crucial for reproducible sensor fabrication and potentially large-scale industrial applications. As the standard substrate for surface acoustic wave (SAW) filters, it guarantees exceptional material consistency and stability, which is crucial for reproducible sensor fabrication and potentially large-scale industrial applications. Typically, the thickness direction of the wafer is known as the y -axis, and the length-cutting directions can be the x - and z -axes. For each direction, there are two types of the electric field: when the length is positioned along the x -axis, the electric field can be along the z -axis or the y -axis; conversely, when the length is cut along the z -axis, the electric field can be along the x -axis or the y -axis. Table 1 presents the standard statistics related to the 128° Y - X -cut LN wafer.

Figure 2 illustrates a comparison of the admittance curves of LNTF under different electric field settings. In the legend, the first letter represents the length-cutting direction, and the second letter means the electric field-loading direction, e.g., z - x indicates that the length is cut along the z -axis and the electric field is placed along the x -axis.

Figure 2 reveals that different electric field-loading approaches produce notable changes in the piezoelectric response characteristics of LNTF, leading to a shift in the resonant frequency. Specifically, for LNTF with its length along the x -axis, when given to an electric field along the y -axis and z -axis, the amplitude of the admittance curve is an order of magnitude lower than that of LNTF with its length along the z -axis (x -axis: 10^{-7} , z -axis: 10^{-6}), and the quality

Table 1 Parameters of the 128° Y - X -cut LN wafer

Density (kg/m ³)	Young's modulus (GPa)	Curie tem- perature (°C)	Piezoelectric coefficient (C/N)	Poisson's ratio
4640	170	1143	$d_{31} = -0.1 \times 10^{-11}$ $d_{23} = -28 \times 10^{-12}$ $d_{24} = 7 \times 10^{-11}$ $d_{33} = 19.22 \times 10^{-11}$	0.25

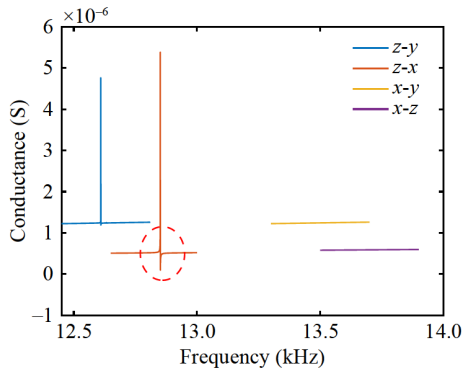


Fig. 2 Comparison of admittance curves of LNTF under different electric fields.

factor is significantly smaller compared to the z -axis orientation. This implies an obvious inhibitory influence of the y/z -axis electric fields on the electromechanical coupling efficiency of X -cut LNTF. The admittance curve under z - x excitation in Fig. 2 displays a larger amplitude, but it also presents significant parasitic peaks. Therefore, this paper mainly focuses on the comparison of the resonant characteristics of LNTF with its length along the z -axis when excited by electric fields along the y -axis and the x -axis. In the time domain, vibration velocity often represents energy magnitude, whereas in the frequency domain, amplitude is commonly associated. Since simulation calculations are performed exclusively in the frequency domain, to compare the amplitude associated with the first-order in-plane vibration mode, with the length oriented along the z -axis, it is essential to compare the amplitudes of the two interdigital electrodes in the x -direction. As simulation calculations are conducted solely in the frequency domain, it is imperative to use an appropriate method for comparison. In comparing the amplitude of the first-order in-plane vibration mode, a certain condition must be taken into account. Specifically, when the length is aligned with the z -axis, it is imperative to compare the amplitudes of the fork-finger electrodes along the x -direction. Consequently, it is vital to calculate the amplitudes in the x -direction at the tips of the fork-finger electrodes under the z - y and z - x loading approaches, ultimately yielding the results depicted in Fig. 3.

The quality factor of the cantilever beam is^[4]

$$Q = \frac{\omega_0}{\gamma/m_{\text{eff}}}. \quad (12)$$

Substituting it into Eqs. (6) and (8), we can obtain

$$x_{\text{max}} = \frac{aVQ}{2m_{\text{eff}}^2\omega_0^2}. \quad (13)$$

Under the same excitation, the amplitude is proportional to the quality factor, but it is constrained by the resonant frequency and its own electromechanical coupling. However, to a certain extent, this can guide us in device design. Figure 3 shows that when the length is cut along the x -axis,

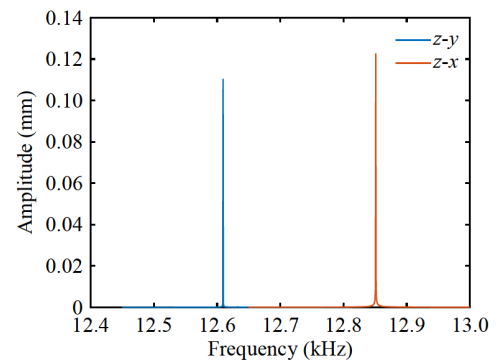


Fig. 3 Amplitudes of LNTF fork-finger in x -direction under different electric fields.

and the electric field is generated along the y -axis, the amplitude in the x -direction at the resonant frequency is larger. This observation is consistent with the description in Eq. (8). Under identical excitation conditions, an increased vibration amplitude leads to an elevation of the admittance magnitude, thereby enhancing the SNR.

Despite the substantially higher admittance curve in the x -direction, as seen by the area encircled by the dashed line in Fig. 2, significant parasitic peaks are present. This results in the appearance of other modes beyond the first-order in-plane bending vibration mode, which hampers its utility as a sensor for measuring fluid properties.

In conclusion, simulations and computations of the admittance curves were performed. These curves were calculated under different electric fields, corresponding to measurements along the z - and x -axes. When we set the length along the x -axis and placed it in electric fields along the y - and z -axes, the amplitude of the admittance curve decreased. Compared with the case when the length was in the z -direction, this decrease was significant. Furthermore, the quality factor in that situation was markedly lower than that of the Z -cut. This indicates that an apparent inhibitory influence of the y/z -direction electric fields on the electromechanical coupling efficiency of the X -cut wafer. When the cutting direction is along the z -axis, and the electric field is loaded along the y -axis, the first-order in-plane bending vibration mode works well. Although the substantial admittance curves in the x -direction, the presence of significant parasitic peaks makes it unsuitable for application as a fluid sensor. For subsequent simulation calculations, the electrode design will be carried out with the length cut along the z -axis and the electric field loaded along the y -axis.

4 Optimal electrode configurations

4.1 Typical electrode configurations

There are typically six electrode configurations for the z - y circumstance. This study examines six electrode configurations for the Z - Y -cut orientation. Among these, the

single-sided and embedded electrode designs have been previously reported in the literature; the remaining four novel configurations are proposed in this work. The specific structural layouts of these six configurations are detailed as follows. Firstly, for the single-sided electrode in Fig. 4, the positive and negative electrodes are located on the same surface side.

Figure 5 illustrates the schematic diagrams of the six electrode configurations. (a) Single-sided electrode configuration, the same as Fig. 4; (b) Single-sided + suspended electrode configuration: constructing on a single-sided electrode structure, a complete metal electrode is positioned on the opposite side to function as the middle electrode potential; (c) Embedded electrode configuration; for measuring conductive fluids, an embedded electrode configuration may be utilized, in which electrodes are positioned between two layers of LNTF to prevent electrochemical corrosion and polarization interference resulting from direct contact between the electrodes and the fluids; (d) Embedded + suspended electrode configurations: based on the embedded electrode configuration, metal electrodes are positioned on one side of the surface; (e, f) Double-sided electrode: a

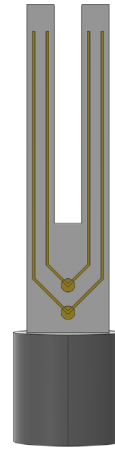


Fig. 4 Schematic diagram of the single-sided electrode configuration for LNTF.

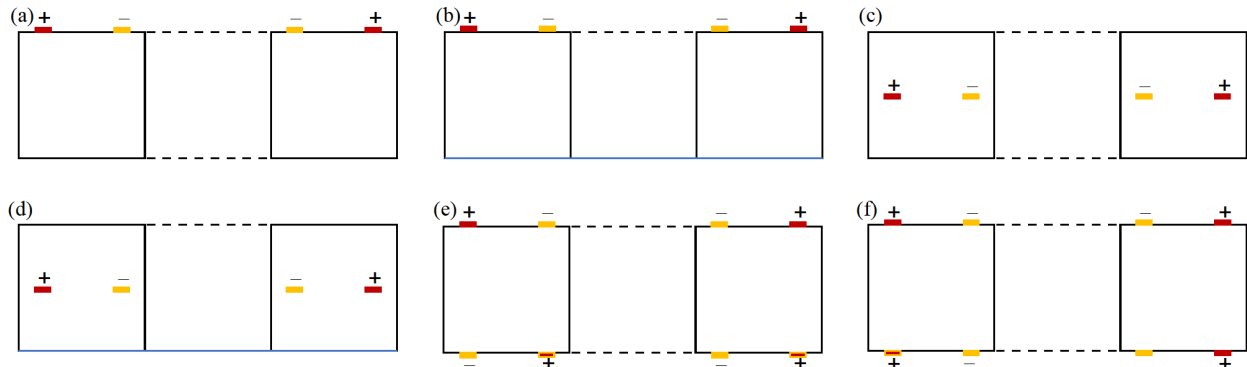


Fig. 5 Schematic diagrams of six electrode configurations: (a) Single-sided; (b) Single-sided + suspended; (c) Embedded; (d) Embedded + suspended; (e) Double-sided electrode 1; (f) Double-sided electrode 2.

single-sided electrode is positioned on both sides, categorized into two types based on the placement of positive and negative electrodes.

4.2 Analysis of the LNTF admittance curve

The admittance curve (shown in Fig. 6) is obtained by performing a twenty-times logarithmic transformation (i.e., $20\lg|Y|$) on the numerical simulation results of the impedance characteristics of the LNTF sensor^[17].

The resonant behaviors of the LNTF are illustrated in Fig. 6. At a particular frequency of mechanical resonance, the amplitude of mechanical vibration reaches its peak; meanwhile, the electrical impedance also displays a minimum value. This frequency is generally recognized as the resonant frequency, denoted as f_r . At this stage, the sensor is in a low-impedance state primarily influenced by mechanical energy, enabling efficient transfer between electrical and mechanical energy. At the anti-resonant frequency f_a , the parallel resonance between the dynamic branch and the static capacitance leads to a marked reduction in mechanical vibration. Consequently, the electrical impedance peaks, and the sensor enters a high-impedance state. The physical features of the frequency space between these two frequencies are determined by the k_{eff}^2 ^[13]. This coefficient is defined as the square of the capacity to transform mechanical energy into electrical energy, and its formula is

$$k_{\text{eff}}^2 = \frac{f_a^2 - f_r^2}{f_a^2} = 1 - \frac{f_r^2}{f_a^2}. \quad (14)$$

This parameter has significance in the design of piezoelectric sensors, including filters and transducers, as it directly influences the bandwidth and energy loss of the sensors. A higher number signifies enhanced energy conversion efficiency of the sensor between resonant and anti-resonant modes, hence permitting a broader operational bandwidth and reduced loss. The frequency spacing between f_r and f_a is a direct indicator of the sensor's excitation efficiency. Increased spacing signifies enhanced efficiency in electromechanical energy conversion. The piezoelectric performance of LN surpasses that of quartz, mainly due to its

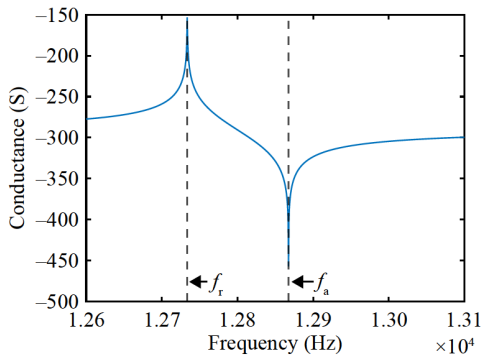


Fig. 6 Admittance curve of LNTF.

greater frequency spacing. Reference [18] addresses a TF sensor made from a quartz crystal, which is cut by rotating 1° along the x -axis. The parameters from this sensor are applied for numerical simulation in this paper. Figure 7 illustrates that two TFs, identical in size and structure but composed of different materials, exhibit mechanical coupling efficiency values of 0.0541 and 0.0018, respectively. The mechanical coupling efficiency of the LNTF sensor significantly surpasses that of the quartz TF (QTF) sensor.

4.3 Comparison of six electrode configurations' performances

Figure 8 shows the admittance curves of the six electrode configurations that were calculated for this work at room temperature. Single-sided, single-sided + suspended, embedded, embedded + suspended, double-sided electrode 1, and double-sided electrode 2 are represented by the legends 1 through 6. The graphic makes it evident that the resonance frequency shifts slightly depending on the electrode configuration of the LNTF.

The admittance curves of the LNTF under six electrode configurations mounting ways are now being compared. The obtained data must undergo frequency-shifting processing to precisely align the peaks of all admittance curves at the resonant frequency f_r . All data are only shifted in frequency

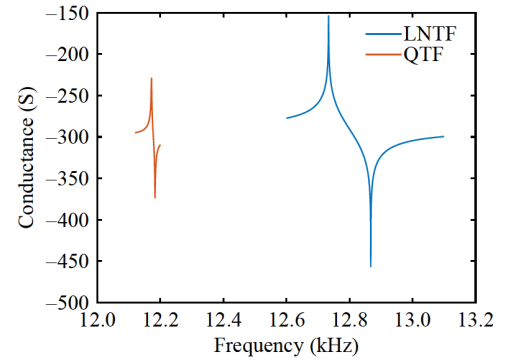


Fig. 7 Comparison of admittance curves of QTF and LNTF.

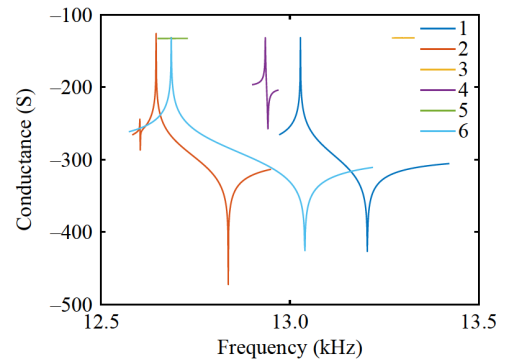


Fig. 8 The LNTF admittance curves with six electrode configurations.

without any other changes. This will allow for an easy and precise comparison of the k_{eff}^2 corresponding to each mounting method. Figure 9 displays the frequency-shifted results, showing that the double-sided electrode configuration 2 has comparatively high excitation efficiency, followed by the single-sided + suspended configuration. The k_{eff}^2 for each electrode configuration can be calculated based on the values of f_r and f_a , with specific outcomes displayed in Table 2. The table indicates that the excitation efficiency of the double-sided electrode configuration 2 installation exceeds that of the other five ways significantly.

4.4 Optimization of electrode structure

This study attempts to improve the excitation efficiency and overall performance of the LNTF in high-temperature fluid measurement applications. Initially, according to the findings in Table 2, single-sided, single-sided + suspended, and the double-sided electrode configuration 2, which demonstrate superior excitation efficiency, are identified as the primary optimization focus. A comprehensive analysis is carried out to examine the impact of two key parameters, the distance between the electrode and the border and the electrode width, on the k_{eff}^2 . This study attempts to improve the excitation efficiency and overall performance of the LNTF in high-temperature fluid measurement applications. The objective is to enhance the k_{eff}^2 through the optimization of specific electrode characteristics. This will enhance the sensor's electromechanical energy conversion efficiency and excitation performance.

However, in practical device design, these two parameters are not independent; rather, they exhibit strong physical and geometric coupling. On one hand, the electrode width and spacing collectively govern the electric field distribution and stress concentration patterns within the piezoelectric crystal,

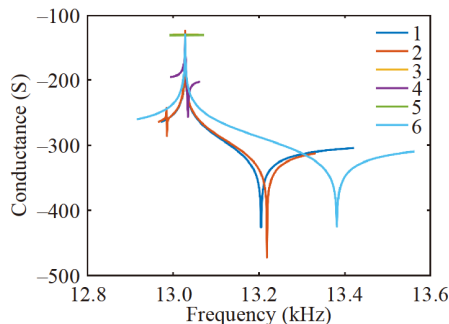


Fig. 9 Admittance curves (frequency shift) of six electrode configurations of LNTF.

Table 2 The k_{eff}^2 of six electrode configurations of LNTF

	1	2	3	4	5	6
$f_a - f_r$	177	191	1	7	1	354
k_{eff}^2	0.0266	0.0295	0.0002	0.0011	0.0002	0.0536

making single-variable optimization insufficient to identify the global optimum under their combined influence. On the other hand, due to the fixed width of the TF arm ($h = 1$ mm) and the need for a symmetrical electrode layout, the geometric parameters must satisfy the strict physical constraint: $2 \times W + 2 \times S + \text{Gap} = h$, where W and S are width and spacing, respectively. Given this limitation, a conventional full-matrix parameter sweep, such as simultaneously maximizing width and spacing, would lead to geometric interference. To address this, this study employed a constrained 2D parametric sweep strategy. A discretized parameter matrix was constructed, and multiphysics simulations were performed only for geometrically feasible combinations. This approach allowed us to exclude invalid geometric regions and precisely map the 2D distribution of the electromechanical coupling coefficient, thereby identifying the global optimal dimensions for each electrode configuration.

Figure 10 displays the discrete heatmaps of the k_{eff}^2 for the single-sided, single-sided suspended, and double-sided electrode 2 configurations under geometric constraints. The gray triangular area in the upper-right corner represents geometrically infeasible areas where the combined electrode width and spacing exceed the physical limit of the TF arms. As shown by the color gradient, the “hot spots” marked by dark red circles correspond to regions of higher excitation efficiency.

A consistent trend is observed across all three configurations: k_{eff}^2 generally increases as the electrode spacing decreases, owing to the enhanced electric field intensity near the electrode edges. Notably, at the parameters set of $W = 0.1$ mm and $S = 0.1$ mm, all three electrode configurations exhibit a distinct local maximum in electromechanical coupling. In Figs. 10(a) and 10(b), the coordinate (0.1, 0.1) lies within a high-efficiency deep-red zone. In Fig. 10(c), the double-sided electrode configuration 2 achieves a significantly higher k_{eff}^2 at this specific coordinate compared to the other configurations, further confirming its superior performance. Therefore, balancing the goals of maximizing excitation efficiency and ensuring fabrication reliability, such as maintaining adequate alignment tolerances, the parameter combination $W = 0.1$ mm and $S = 0.1$ mm is identified as the optimal and rational design choice for subsequent device fabrication. To further validate the identified optimal parameters, the same constrained 2D parametric sweep method was employed to evaluate the maximum displacement at resonance. By analyzing the displacement distribution within the same geometric constraints, we seek to determine whether the high-efficiency region in terms of k_{eff}^2 translates into a robust mechanical response.

Figure 11 presents the constrained 2D optimization results for the maximum displacement amplitude of the three TF sensor configurations. The displacement amplitude distribution aligns with that of the electromechanical

coupling coefficient k_{eff}^2 shown in Fig. 10, further supporting the direct correlation between excitation efficiency and mechanical output. In particular, when both the electrode width and spacing are optimized to 0.1 mm, all three sensor designs attain their maximum or near-maximum vibration amplitudes within the feasible design space. Figure 11(a) shows that the single-sided electrode configuration yields a displacement of about 1.8 nm. Figure 11(b) indicates that the single-sided suspended structure substantially enhances the

vibration, achieving a peak amplitude of approximately 4.5 nm at the (0.1, 0.1) coordinate. Figure 11(c) demonstrates the pronounced superiority of the double-sided electrode configuration 2, which reaches an amplitude of about 14 nm under the same optimized geometry ($W = 0.1$ mm, $S = 0.1$ mm). This configuration demonstrated the highest vibration performance, with an amplitude roughly three times that of the suspended structure and 7.7 times that of the conventional single-sided structure.

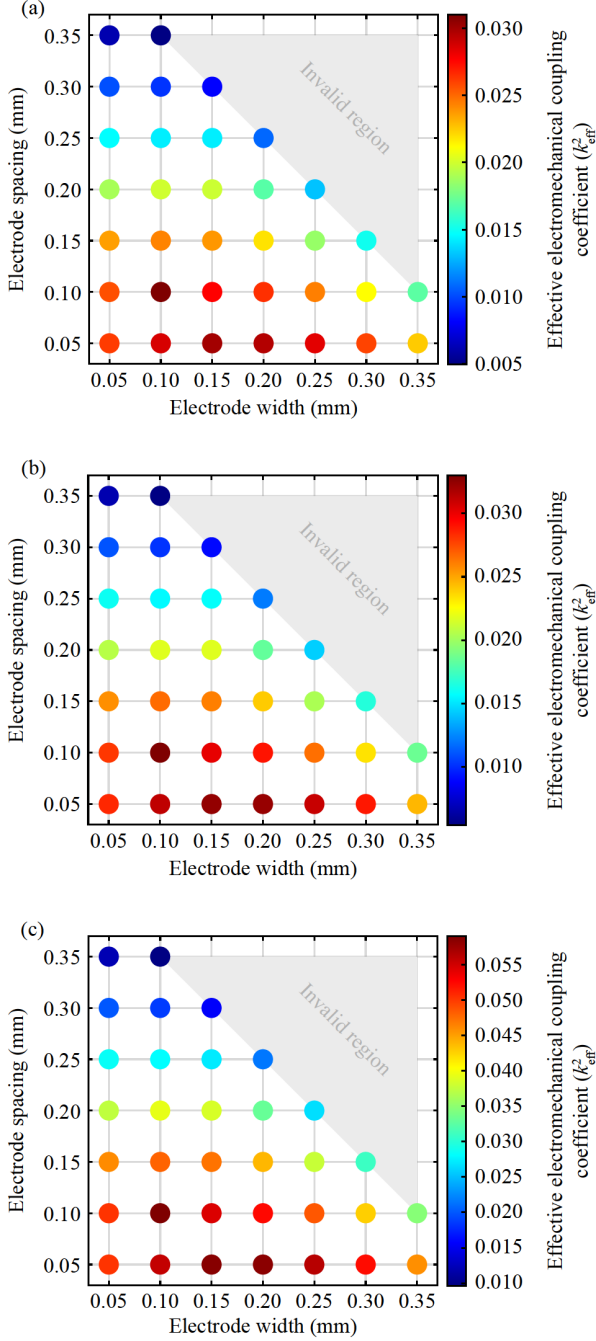


Fig. 10 Constrained 2D joint optimization results of the k_{eff}^2 for different electrode configurations: (a) Single-sided; (b) Single-sided + suspended; (c) Double-sided electrode 2.

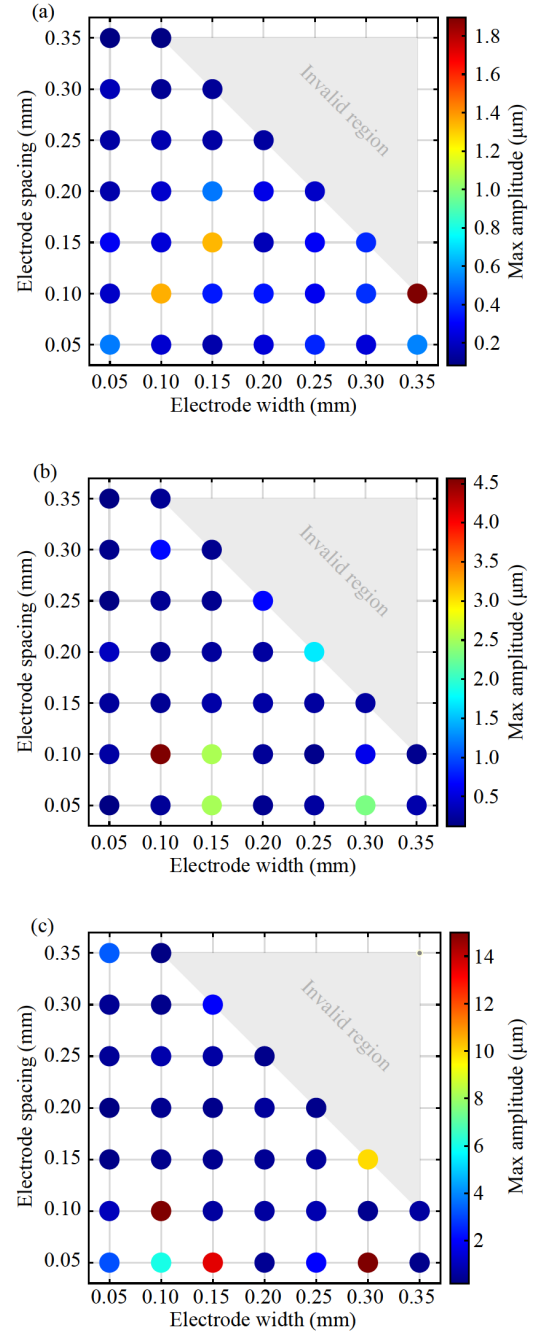


Fig. 11 Constrained 2D joint optimization results of the maximum vibration amplitude at resonance for different electrode configurations: (a) Single-sided; (b) Single-sided + suspended; (c) Double-sided electrode 2.

This result definitively demonstrated that the double-sided electrode configuration 2, together with the optimized parameters ($W = 0.1$ mm, $S = 0.1$ mm), provides the strongest driving capability for high-viscosity fluid measurements. Accordingly, an electrode width and spacing of 0.1 mm were chosen for the subsequent fabrication of the electrodes. It is important to note that the optimal electrode configuration identified in this study is determined from a 128° Y - X -cut LN substrate and a millimeter-scale TF geometry. Given the strong anisotropy of LN, this optimal ratio provides a reliable design guideline for sensors operating at similar dimensional scales (millimeter scale) and under comparable crystallographic orientation. If the aspect ratio of the TF is altered with shorter and thicker tines, both the mechanical stiffness and resonant frequency will shift. Nevertheless, the underlying trade-off mechanism between electric field intensity (which benefits from reduced spacing) and effective actuation area (which is enhanced by optimized electrode coverage) remains fundamentally unchanged. As a result, the proposed electrode configuration continues to be effective across variations in arm geometry. Conversely, if the crystallographic cut is fundamentally changed to Z -cut or X -cut, the dominant piezoelectric coefficients in the constitutive matrix will differ. This may require re-optimizing the electrode topology to align the electric field with the new axis of maximum electromechanical coupling. Consequently, although the methodology of the constrained parametric sweeping is universally applicable, the specific optimal parameters should be reassessed when scaling to micro- or nano-scale dimensions or when employing alternative substrate cuts.

5 Effect of temperature

The LN has extensive potential applications in sensor technology owing to its unique physical characteristics. However, a notable shift in parameters with temperature is observed, especially with small sensors^[19]. Due to the compact structure and limited space of small sensors, the electrode structure has a non-negligible impact on the performance of materials in high-temperature environments. The LNTF sensors are extensively utilized in practical applications for monitoring the properties of high-temperature fluids. The operation of the electrode installation technique in high-temperature conditions is essential for guaranteeing the precision and reliability of measurement outcomes. To evaluate and improve LNTF performance under extreme temperature circumstances, it is essential to analyze the temperature drift characteristics of LNTF sensors in such environments. This study seeks to understand the inherent relationship between electrode installation ways and changes in temperature. The research aims to evaluate the performance stability of different electrode configurations at

different temperatures. The paper calculates the admittance curves of six electrode configurations from room temperature (20°C) to 180°C , obtaining their resonant frequencies and quality factors. Figure 12 shows the admittance curves of the LNTF with the double-sided electrode configuration 2 at two different temperatures.

As shown in Fig. 12, as the temperature increases, the admittance curve shifts towards lower frequencies, and the space between f_r and f_a also changes. This study simulates and calculates the variation in resonant frequency with temperature for LNTF sensors across six electrode structures within the range of 20 – 180°C .

The objective is to quantify the impact of different electrode configurations on the device's temperature drift characteristics. Figure 13 demonstrates that as the temperature rises from 20°C to 180°C , the resonant frequencies of LNTF sensors with six electrode configuration modes follow a consistent decreasing trend. Due to the highly consistent variation trends of double-sided electrode configurations 1 and 2, the green curve overlaps with the other curve and is therefore not clearly visible in the figure.

The TCF for six electrode configurations is calculated using room temperature as the reference point. Linear regression is utilized to establish the slope of frequency variation relative to temperature, producing specific results

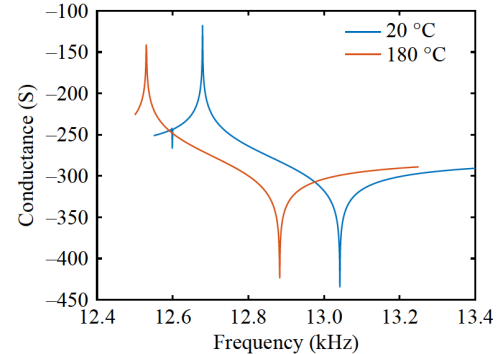


Fig. 12 The admittance curves of the LNTF featuring the double-sided electrode configuration 2 at two different temperatures.

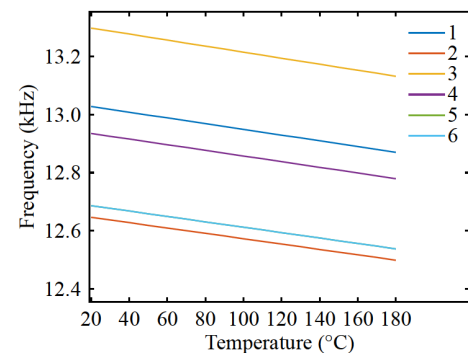


Fig. 13 The resonance frequency of the LNTF sensor, including six electrode configurations, changes with temperature.

as presented in Table 3.

$$\text{TCF} = \frac{f(T) - f_0}{f_0 \times (T - T_0)} \times 10^6. \quad (15)$$

The analysis of the resonant frequency shift rate induced by temperature (Table 3) reveals striking differences in the response characteristics for different electrode configurations to thermal disturbances. The embedded electrode structure demonstrates the largest resonant frequency temperature shift ($\text{TCF} = -78.07 \text{ ppm}/^\circ\text{C}$), suggesting its strong thermal sensitivity. The single-sided + suspended electrode structure exhibits the lowest resonant frequency temperature shift ($\text{TCF} = -73.01 \text{ ppm}/^\circ\text{C}$), indicating superior thermal stability over the evaluated temperature range.

The calculated quality factor variation with temperature for LNTF sensors across six electrode configurations is shown in Fig. 14. The electrode structure numbers (six total) are listed on the x-axis, while the percentage change relative to 20°C is shown on the y-axis.

The most stable performance under high-temperature settings corresponds to the double-sided electrode configuration 2, which shows the minimum temperature drift in quality factor (around 6.06%). With a temperature drift of roughly 6.67%, the double-sided electrode configuration 1 comes next, displaying some resistance to temperature changes. The embedded electrode configuration, on the other hand, exhibits noticeably higher temperature drift (39.89%), suggesting greater sensitivity to temperature effects and less stability at high temperatures.

Table 3 Six electrode configurations corresponding to the TCF

Electrode configuration number	1	2	3	4	5	6
TCF (ppm/ $^\circ\text{C}$)	-75.65	-73.01	-78.07	-75.28	-73.32	-73.32

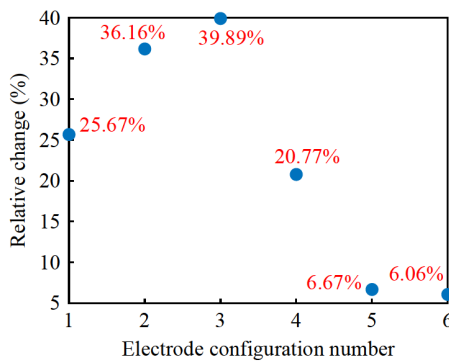


Fig. 14 Temperature-dependent changes in the quality factor of the LNTF sensors with six different electrode configurations.

6 Experimental verification

6.1 Experiment in the air

Since the embedded, embedded + suspended, and

double-sided electrode configuration 1 electrode installation methods have low excitation efficiency problems and embedded and embedded + suspended require intricate fabrication procedures like wafer bonding and through-silicon via (TSV) technology, this study only chooses the other three installation methods for physical fabrication. The surface electrode plating is primarily conducted through the plasma-enhanced chemical vapor deposition (PECVD) process, utilizing aluminum electrodes with a thickness of $2 \mu\text{m}$. Three types of TF sensors are built based on the results of prior simulation analyses, and the electrode sizes for all three types of TF sensors utilize the optimization results obtained in the previous sections. Following bottom fixation, the admittance curves of LNTF at room temperature are measured using an impedance analyzer, with the physical LNTF and the experimental data illustrated in Fig. 15. Throughout the experiment, essential variables, including supply voltage and environmental parameters, are meticulously maintained for the reliability of the comparative analysis.

Figure 16 presents the measured admittance curves for the three different electrode configurations and a standard QTF^[20] in air. The resonant frequencies and quality factors can be derived from the admittance curves, as presented in Table 4. Meanwhile, the previous calculations (Eqs. (8) and (12)) and simulation results can be verified. Specifically, the double-sided electrode structure 2 exhibits a high k_{eff}^2 .

As can be observed from the figure, it also has the highest admittance curve magnitude, indicating a relatively large amplitude. Under the same excitation and external damping conditions, the double-sided electrode configuration 2 also achieves a relatively high quality factor. Figure 16 depicts the admittance curve of a QTF in air. To enhance visual clarity, all curves have been shifted in frequency relative to the QTF, while other parameters remain unchanged. The amplitude of the admittance curve for the QTF is significantly smaller than that of any type of LNTF.

Under identical experimental conditions, the quality factor of the double-sided electrode configuration 2 is superior to the other two comparative configurations, with magnitude

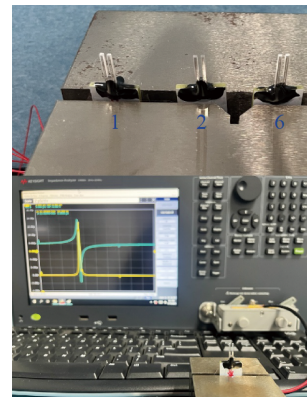


Fig. 15 Physical diagram of the LNTF sensor and measurement system with three types of electrode configurations.

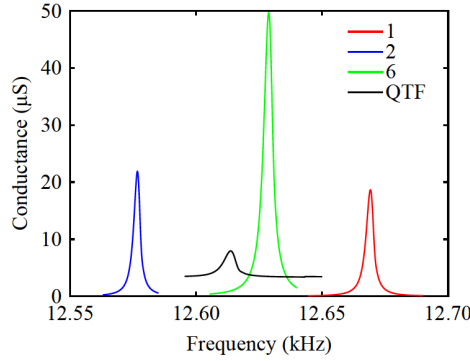


Fig. 16 Measured admittance curves of LNTF with three different electrode configurations.

Table 4 Three different electrode configurations for LNTF's resonant frequency and quality factor

Electrode configuration number	1	2	6	QTF
Resonant frequency (kHz)	12669.12	12576.62	12563.60	32747.60
Quality factor	5361.00	6152.48	6411.79	5128.67

differences demonstrating strong alignment with previous simulation predictions. The experimental result confirms the high efficiency of the double-sided electrode configuration 2 in enhancing electromechanical coupling efficiency, thus improving the overall performance of the TF sensor. Under the same excitation, the quality factors of three LNTFs are higher than that of QTF, which proves that LNTFs have a higher electromechanical coupling coefficient.

6.2 Experiment in several standard oils

The resonant frequency and quality factor of a TF vibrating in a fluid are related to the density and viscosity of the fluid^[21]:

$$\begin{cases} \frac{\omega_{\text{vac}}^2}{\omega_1^2} - 1 = a_0 \rho_1 + a_1 \sqrt{\frac{\mu \rho_1}{\omega_1}}, \\ \frac{1}{Q_v} \frac{\omega_{\text{vac}}^2}{\omega_1^2} = b_1 \sqrt{\frac{\mu \rho_1}{\omega_1}} + b_2 \frac{\mu}{\omega_1}, \end{cases} \quad (16)$$

where ω_1 and Q_v represent the angular resonant frequency and the quality factor of the TF in the fluid, respectively. ρ_1 and μ are the density and dynamic viscosity of the fluid. a_0 , a_1 , b_1 , and b_2 are the calibration coefficients associated with the fluid added mass and viscous damping effects. ω_{vac} denotes the intrinsic angular resonant frequency of the TF in a vacuum, which is determined by the material properties and structural configuration:

$$\omega_{\text{vac}} = \frac{h}{2\sqrt{3}} \sqrt{\frac{E}{\rho}} \left(\frac{1.875}{L} \right)^2, \quad (17)$$

where E is the Young's modulus of the material, and ρ is the density of the TF material. L and h refer to the length and width of the TF arm, respectively. The fluid Reynolds

number (Re) characterizes the flow regime and is defined as $Re = \rho_1 \omega_1 e^2 / (4\mu)$, where e is the thickness of the TF arm.

In the first equation of Eq. (16), the fluid density term is dominant, indicating that the resonant frequency shift is mainly influenced by the fluid density. This behavior corresponds to the “added mass effect”, in which fluid adhering to the TF surface oscillates in sync with it, thereby increasing the sensor's effective mass. The second equation in Eq. (16) describes the energy dissipation resulting from the TF's vibration in the fluid. The right-hand side of this equation depends largely on the fluid viscosity μ . Fluids with higher viscosity produce stronger shear stresses during oscillation, converting more mechanical energy into thermal energy. This dissipation accelerates the decay of vibration and leads to a notable decrease in the quality factor.

To validate the performance of the aforementioned optimized designs in fluid media, experimental tests were conducted using five standard reference oils: N10, N100, N140, S20, and S60 at five temperature points. Figure 17 shows the schematic diagram of the experimental setup. Table 5 lists the density and viscosity values of five standard oils at 25 °C.

Figure 18 shows the measurement results of four TFs in five standard oils. Due to the significantly higher resonant frequency of the QTF compared to the LNTFs, it was impossible to display both curves within a single frequency range. To enable direct comparison, a frequency offset was applied to the quartz data, aligning its operational range with that of the LNTFs. The quality factors of four TFs in five standard oils at 25 °C are calculated in Table 6.

From the tabulated data, it is evident that the LNTF sensors exhibit higher Q factors in fluid compared to QTFs,



Fig. 17 Schematic diagram of standard oil experiment.

Table 5 Density and viscosity of five standard oils at 25 °C

	N10	N100	N140	S20	S60
Density (g/cm ³)	0.8596	0.8742	0.8345	0.8555	0.8619
Viscosity (cP, 1 cP = 10 ⁻³ Pa·s)	13.45	189.50	247.10	30.08	100.90

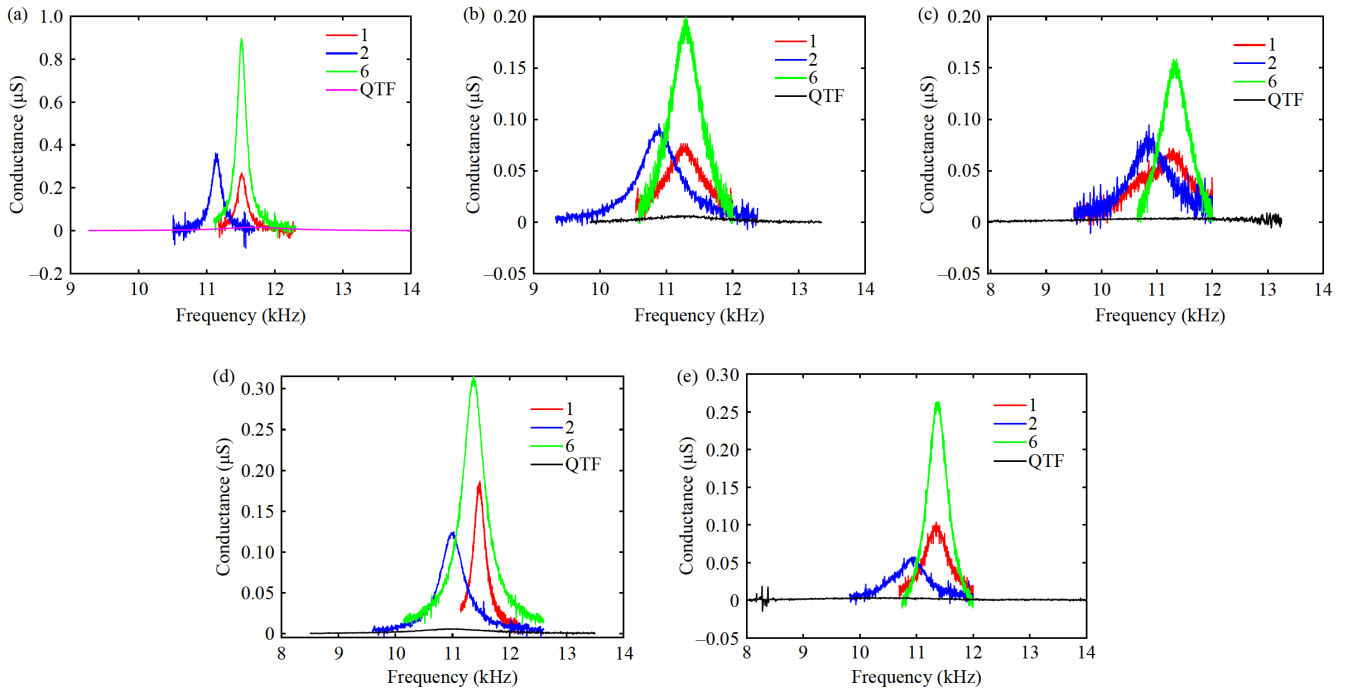


Fig. 18 Admittance curves of TF sensors in five standard oils at 25 °C: (a) N10; (b) N100; (c) N140; (d) S20; (e) S60.

Table 6 Quality factors of four TFs in five standard oils at 25 °C

	N10	N100	N140	S20	S60
1	98.80	24.27	18.02	32.84	25.63
2	110.37	28.79	25.08	35.11	29.06
6	122.36	32.82	28.68	38.26	37.99
QTF	36.55	12.69	—	29.38	15.01

accompanied by larger admittance curve amplitudes and improved SNRs. These characteristics facilitate the accurate extraction of both Q and resonant frequency. Specifically, at a viscosity of 247.1 mPa·s, the admittance curve of the QTF becomes obscured by noise, making it impossible to determine the resonant frequency and quality factor. As a result, the sensor ceases to function under these conditions. In contrast, even in high-viscosity N140, the optimized sensors maintain clearly discernible resonance peaks. Among them, the double-sided electrode configuration 2 exhibits the narrowest bandwidth, with the suspended and single-sided types in sequence—a finding that is fully consistent with simulation results.

While the Q values of various LNTF configurations show minimal variation under high-viscosity conditions, the double-sided electrode 2 demonstrates superior Q performance in low-viscosity regimes, consistent with simulation predictions, indicating enhanced sensitivity. This configuration also maintains higher overall admittance amplitudes (improved SNR) and lower mechanical impedance, enabling more efficient energy coupling to the primary vibrational mode.

Building upon the initial performance evaluation at 25 °C, the experimental scope was extended to assess the accuracy of density and viscosity inversion across a broader range of temperatures. Admittance curves for all TF sensors were measured in five standard oils at elevated temperatures of 40, 50, 80, and 100 °C.

Figure 19 clearly illustrates the evolution of admittance characteristics for the four TF sensors immersed in N10 standard oil. A consistent trend is observed across all configurations: as the temperature increases from 25 °C to 100 °C, accompanied by a corresponding decrease in fluid density and viscosity, the admittance curves exhibit both a reduction in amplitude and a redshift in resonant frequency, i.e., a shift towards lower frequencies. Under all temperature conditions, the double-sided electrode 2 LNTF (Fig. 19(d)) consistently exhibits the highest peak conductance amplitude.

The amplitude of double-sided electrode configuration 2 (Fig. 19(d)) exceeds that of single-sided suspended electrode configuration (Fig. 19(b)) by more than twice, and is also more than 30 times that of traditional QTF (Fig. 19(a)). This notably strong signal response indicates that the double-sided electrode configuration 2 maintains a high SNR even at elevated temperatures, offering a reliable basis for high-precision density and viscosity inversion.

Based on the measured curves, the resonant frequency and quality factor were determined and used to invert the fluid density and viscosity according to the established model. The inversion errors were subsequently calculated

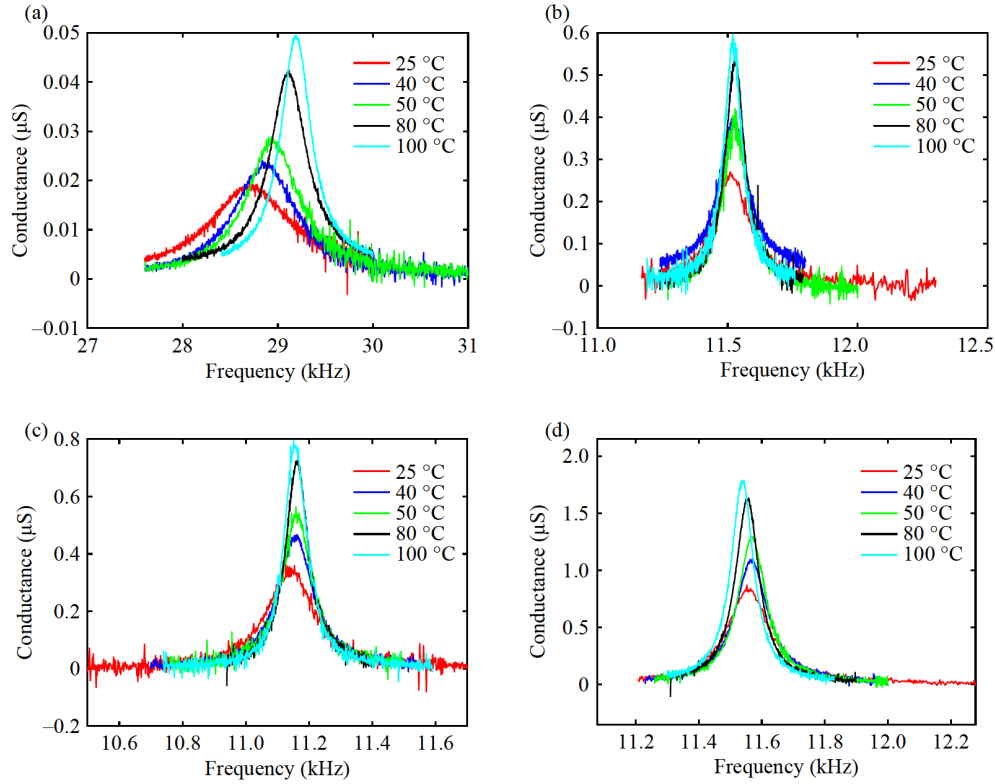


Fig. 19 Temperature-dependent conductance curves of the four TF sensors in N10 standard oil: (a) QTF; (b) Single-sided; (c) Embedded + suspended; (d) Double-sided electrode 2.

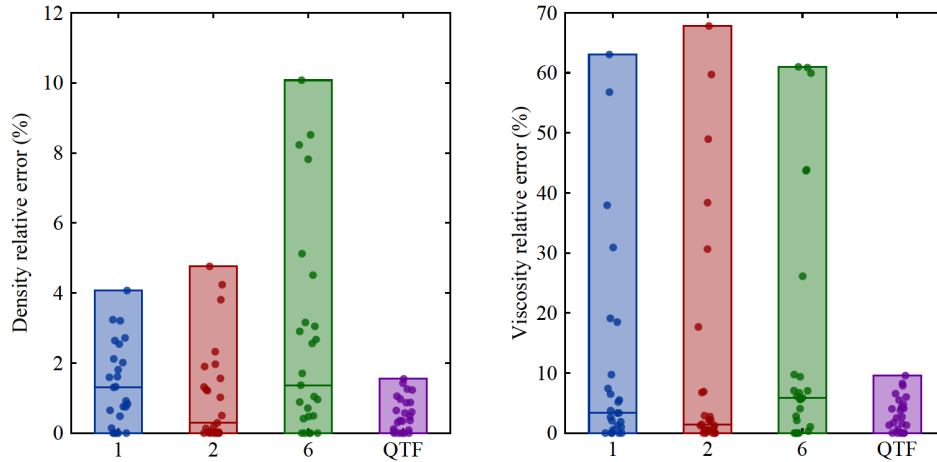


Fig. 20 Relative error of density and viscosity inversion before temperature calibration.

to provide a comprehensive assessment of the sensors' measurement reliability over the tested temperature range. The inversion error results of density viscosity before and after temperature calibration are shown in Figs. 20 and 21, respectively.

As established in previous studies, QTF possessed inherent thermal stability with a low temperature coefficient of frequency, leading to a negligible drift in both frequency and quality factor^[21]. Therefore, no temperature correction was applied to the QTF data, which served as a baseline

reference. In contrast, LNTFs are recognized for their high thermal sensitivity. As shown in Figs. 20 and 21, this characteristic is clearly observed. Before correction (Fig. 20), all three LNTF configurations exhibited substantial deviations caused by thermal cross-sensitivity, with relative errors in viscosity exceeding 60%, significantly greater than that of the uncorrected QTF (approximately 10%). After implementing the temperature compensation algorithm, however, the performance of the LNTF sensors improved markedly (Fig. 21). The relative errors in density for all

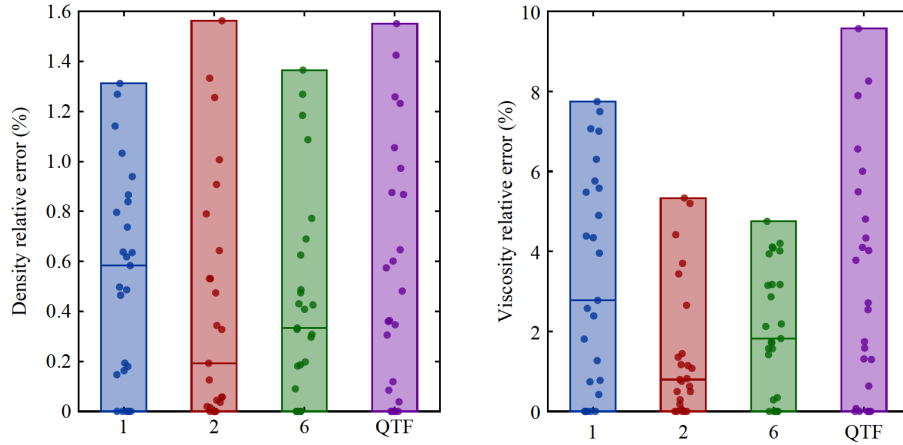


Fig. 21 Relative error of density-viscosity inversion after temperature calibration.

sensors decreased to a low level ($<1.6\%$), indicating strong mass sensitivity. In terms of viscosity relative errors, the corrected double-sided electrode configuration 2 LNTF (group 6) exhibited particularly high accuracy, with its maximum error falling below 4.8% . This corresponds to a reduction of about 50% compared to the uncorrected QTF (approximately 9.6%). These results demonstrate that although the LNTF inherently suffers from notable thermal drift in fluids under varying temperatures, the geometrically optimized double-sided electrode configuration 2 LNTF, when used in conjunction with thermal compensation, achieves a measurement precision superior to that of the conventional QTF.

7 Conclusion

The paper analyzes the optimization of electrode design for TF sensors made from 128° Y-X-cut LN (LiNbO_3) single crystals. Subsequently, the influence mechanisms of six electrode configurations (single-sided, single-sided + suspended, embedded, embedded + suspended, double-sided electrode 1, double-sided electrode 2) on the electro-mechanical response characteristics under the first-order in-plane bending modes are analyzed. This analysis is carried out by means of piezoelectric constitutive equations, thermoelastic coupling effects, and interface contact models through numerical simulation. The influence of six electrode configurations on the k_{eff}^2 of LNTF sensors is quantitatively evaluated. Physical sensor specimens are fabricated for experimental validation.

These results indicate that the in-plane first-order bending vibration mode functions effectively when the cutting direction is aligned with the z-axis and the electric field is oriented along the y-axis. Although the admittance curve in the x-direction is large, it has distinct parasitic peaks, rendering it unsuitable for use as a fluid sensor. The double-sided electrode configuration

2 exhibits the highest performance. Regarding the geometric dimensions, the optimization results indicate that an electrode width of 0.1 mm paired with a spacing of 0.1 mm achieves optimal performance. This configuration maximizes the effective electromechanical transduction efficiency by striking an ideal balance between the electric field intensity and the effective excitation area. Within the temperature range of $20\text{--}180^\circ\text{C}$, the embedded electrode exhibits the largest significant TCF at $-78.07\text{ ppm}/^\circ\text{C}$, signifying the highest thermal sensitivity. Conversely, the single-sided + suspended electrode structure shows the lowest TCF of $-73.01\text{ ppm}/^\circ\text{C}$ and maintains relatively stable performance. The double-sided electrode configuration 2 features excellent electromechanical coupling efficiency, a high quality factor, and reliable high-temperature stability, serving as a reference for LNTF electrode design. The experimental results in air and several standard oils indicate that the quality factor of double-sided electrode configuration 2 is superior to that of other electrode configurations, and all the measured results outperform QTF, and the measured differences are in good agreement with the simulation results. Inversion results demonstrate that LNTF sensors exhibit superior performance to the QTF in terms of both viscosity detection accuracy and dynamic measurement range. Particularly, the double-sided electrode configuration 2 reduces the relative error to nearly half that of the QTF, highlighting its enhanced sensing capability.

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