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Application Note

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Cryogenic Amplifier Enhances Tuning Fork Microscopy

Quartz Tuning Forks in Microscopy

Quartz tuning forks have gained significant attention in microscopy, particularly in atomic force microscopy (AFM) and scanning probe microscopy (SPM), and more recently in scanning tunnelling microscopy (STM). Their unique properties, including high mechanical quality factor (Q factor), robustness, and stability, make them ideal for high-precision measurements and imaging at the nanoscale. Numerous applications have evolved, which reach beyond the scientific world into industrial and analytical usage and has advanced the fields of material science, biology, and nanotechnology possible. See also references [1] to [3].

A special field is the usage of ***cold environments***, enabling new possibilities in scientific research and analytical methods, since a cold ambience (e.g. 4.2 K, liquid Helium temperature) allows for almost noiseless detection of signals with drastically increased sensitivity [4].

Quartz tuning forks operate based on their piezoelectric properties, where mechanical elongation generates an electrical signal. The tuning forks are typically employed in a configuration where one prong is fixed, and the other interacts with the sample surface. The oscillation of the fork is influenced by the tip-sample interaction forces, altering the resonance frequency or amplitude.

However, guiding the tiny signals generated by quartz tuning forks out of a vacuum environment, especially a cryogenic environment, presents several challenges. These challenges primarily stem from the need to preserve signal integrity and minimize noise and interference.

Key problems:

- **Signal attenuation and noise,** the small oscillation signals produced by quartz tuning forks can be easily attenuated and overwhelmed by thermal noise during transmission from the vacuum chamber to external detection. Additionally, triboelectric noise can impair signals during the transition from cryogenic to room temperature cabling.

- **Vacuum feedthroughs** may add further noise due to several metal-to-metal transitions

- **Electromagnetic interference (EMI)** poses another thread to signal quality and integrity, since the protectional effect of shields in cables is always limited, and large interferences in a noisy ambience setup often degrade or overwhelm the tiny tuning fork signal in an unfavourable and often unpredictable way.

A solution for these problems is the usage of a (cryogenic) amplifier, which is being placed in *direct proximity* (say few millimetres) to the tuning fork crystal. After a substantial amount of amplification, all three effects mentioned above become far less pronounced, and this allows for reaping the great benefits that cryogenic tuning fork systems offer.

How to connect the tuning fork to the amplifier

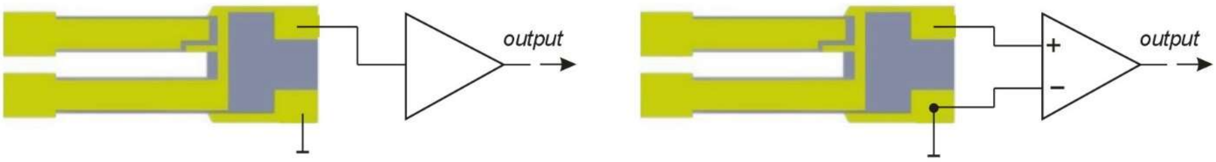

Fig. 1 (left) asymmetric amplification scheme, (right) symmetric amplification scheme for noise cancellation

The simplest way, in which a tuning fork may by connected to an amplifying circuit, is to have one electrical terminal (one prong) grounded, and the other prong in direct connection to an amplifier with shortest possible distance. Even though this scheme is straight forward, it may lead to problematic results in cryogenic setups, since the local ground inside the cryostat may not be well connected (for thermal conduction reasons) to the room temperature part, where further signal processing takes place. This can lead to severely compromised results, especially in noisy or poorly filtered environments. An efficient way to cope with such grounding problems consists of using a differential amplifier (fig. 1, right part). A differential amplifier measures the voltage *difference* (or: current or charge differences, see remark below) at the spot of the signal source, thus mostly avoiding the effects of noise on GND lines, which connect the cold and the warm parts of the setup.

A more comprehensive diagram is shown below. It depicts a DC bias for a probe tip and a weakly coupled AC modulation of the tuning fork. Depending on the tuning fork design, which is often customized, the amplifier may or may be not electrically connected to the sample tip (isolated version depicted below).

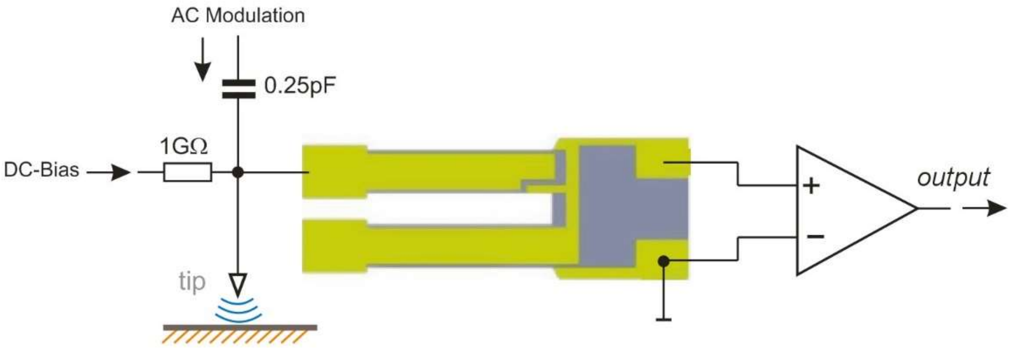

Fig. 2: diagram of AC- and DC-biasing of a probe tip and signal coupling to an amplifier

Type of amplifier to be used

In general, there are three basic types of amplifiers commonly used to detect very small signals: voltage type, charge type, and current type amplifiers. The subsequent pictures indicate some basic circuits to accomplish these functions.

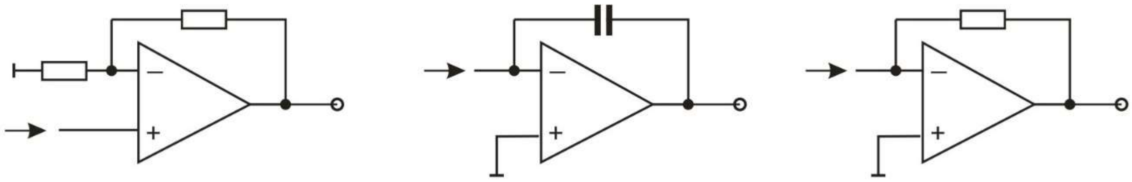

Fig. 3: three basic diagrams for voltage / charge / current amplifiers using a feedback amplifier

Even though these amplifier types appear to function quite differently, their noise properties are actually comparable – at least, when they are optimized with respect to their resistors or capacitors.

The bottom line is that the amplifier's **input voltage noise density u_n and current noise density i_n** are the most relevant quantities at the frequency range of interest [5]. Speaking in physical terms, the current density i_n is a real electrical current arising at the amplifier's input, which is in competition with the AC current (=oscillating charge) generated by the tuning fork.

On the other hand, the voltage noise u_n that in general 'masks' the tuning fork signals rather understood to be a virtual quantity, created inside of each electrical amplifier. Both noise quantities are highly relevant in the context of detecting the very small AC charges of a tuning fork. (Note that the CX-4 is routinely sold in voltage-amplification configuration.)

Electrical signal strength of a tuning fork and competing noise

Given that the mechanical prong elongation of the fork oscillation is chosen to extend only over a small distance (e.g., 10 nm) to probe effects at the scale of single atoms, typical measurable electrical charge quantities amount to about 20 fC (1 fC = 1 femtocoulomb). This charge quantity is proportional to the momentary elongation of the prong of the tuning fork, and can be calculated using the electro-mechanical coupling constant α which is typically 2 µC/m (reported values are 1.44 µC/m [7] to 4.2 µC/m [6]), relating the mechanical motion to a charge displacement.

Now, the goal is to clearly detect this small charge amplitude of 20 fC with a suited amplifier. Since noise quantities of amplifiers come as *densities*, rather than absolute values, one needs to define a certain observation time, or bandwidth respectively. Say for instance 1 Hz bandwidth, i.e. 1 sec. observation time, in order to get an absolute quantity. For rescaling to faster measurements please refer to the literature references at the end of this note.

In other words, in real world setups one observes an amplifier-related *noise charge density* $n_{el,q}$ competing with the tuning fork charge signal. The resulting quantity of **elongation noise n_q** (following $n_q = n_{el,q} / \alpha$) may be the most interesting figure of merit, since it shows the geometrical resolution of the tuning fork elongation, which can be achieved in a specific setup. Several numbers are listed below. Note that the recent scientific publication [7] lists even more measurements and further references and may be used for further inspiration.

	CX-4	**Giessibl [7]**	**300 K commercial 1[*)]**	**300 K commercial 2[*)]**
i_n	4 fA/√Hz	see [7]	100 to ~500 fA/√Hz	25 fA/√Hz
u_n	0.5 nV/√Hz	see [7]	0.7 nV/√Hz	5 nV/√Hz
$n_{el,q}$	24 zC/√Hz (Δf=1Hz, 32 kHz, 8 pF)	35 zC/√Hz (estimated)	~ 90 zC/√Hz (120 pF input cabling)	~ 500 zC/√Hz (120 pF input cabling)
elongation noise n_q (Δf=1 Hz, f = 32 kHz)	12 fm/√Hz (estimated)	24 fm/√Hz (measured)	> 90 fm/√Hz (estimated)	> 300 fm/√Hz (estimated)
cryogenic power load	700 µW	2.2 mW	not applicable	not applicable
total amplification	300 mV/fC (8 pF estimated input load)	6.6 mV/fC	10 mV/fC	10^8 V/A (20 mV/fC at 32 kHz)
operating temperature	< 1 K to ~30 K	~ 4.2 K (and higher)	300 K only	300 K only

table 1: various reported properties for cryogenic electrical detection systems, resulting elongation noise of tuning forks

[*)] Notes: commercial 1: high-grade competitor amplifier (only 300 K operation) for tuning forks
commercial 2: high-grade competitor amplifier (only 300 K operation) for STM applications

Summary

Placing a cryogenic amplifier very close to the signal source, such as a tuning fork is highly beneficial for several reasons. In addition to avoiding the challenges of guiding extremely low-level signals without supporting amplification through cables and feedthroughs, the proximity of the amplifier to the (cryogenic) signal source has the effect of greatly reducing parasitic capacitances. This allows for operating an amplifier like the CX-4 in a simple voltage-amplification mode.

The CX-4 comes as plug-and-play solution including room temperature controller and features a powerful post-amplification stage to obtain large signals (output scaling up to 300 mV/fC), which are easy to process, e.g. by a lock-in amplifier or FFT. The very low heat dissipation, below 1 mW, further eases the integration into a low temperature system in the common temperature range 1 K to 30 K.

For further description and data please refer to our web presence:
https://www.stahl-electronics.com.

Fig. 4: cabling scheme of connecting the differential version of CX-4 to room temperature controller/post-amplifier.

Literature references

[1] Giessibl, F. J. (1996). Atomic Resolution of the Silicon (111)-(7×7) Surface by Atomic Force Microscopy. Science, 267(5194), 68-71

[2] Albrecht, T. R., Grütter, P., Horne, D., & Rugar, D. (1991). Frequency modulation detection using high-Q cantilevers for enhanced force microscope sensitivity. Journal of Appl. Phys., 69(2), 668-673

[3] Garcia, R., & Perez, R. (2002). Dynamic atomic force microscopy methods. Surface Science Reports, 47(6-8), 197-301

[4] Giessibl: AFM's path to atomic resolution, Materials Today Volume 8, Issue 5, May 2005, Pages 32-41

[5] Helmuth Spieler: Front-End Electronics and Signal Processing

Link: https://www-physics.lbl.gov/~spieler/ICFA_Morelia/text/Front_End_Electronics.pdf

[6] https://www.specs-group.com/fileadmin/user_upload/products/application-notes/nanonis/TF2.pdf

[7] Huber, Giessibl, Review of Scientific Instruments 88, 073702 (2017); doi: 10.1063/1.4993737