Università degli Studi di Bari

DIPARTIMENTO INTERATENEO DI FISICA, 'MICHELANGELO MERLIN'

PhD course in Physics – XXXIV cycle

Study of the electro-thermal properties and acoustic coupling of quartz tuning forks

Tutors:
Prof. Vincenzo Spagnolo
Dott. Pietro Patimisco

PhD student:

Stefano Dello Russo

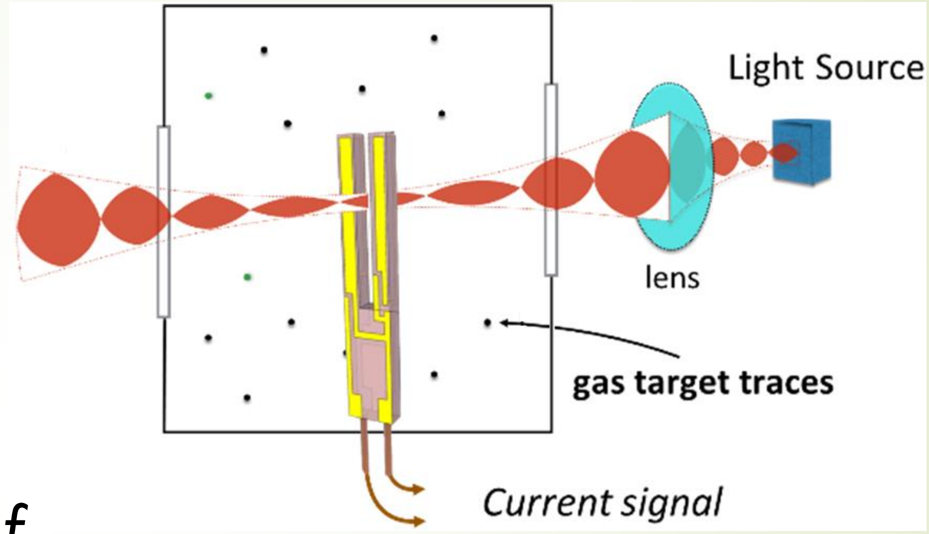
First year report

Outline

- Introduction to QEPAS
- **Custom quartz tuning forks** design and implementation
- QTF – mR **acoustic coupling** analysis
- Gas matrix effective **relaxation rate** measurements
- **Interferometric PAS** with custom QTFs

Quartz-Enhanced Photoacoustic Spectroscopy

- Optical LASER absorption
- Non-radiative relaxation through molecular collisions
- Acoustic wave generation
- Detection of the acoustic signal S with a QTF



$S = CP\alpha Q$ $Q = f/\Delta f$

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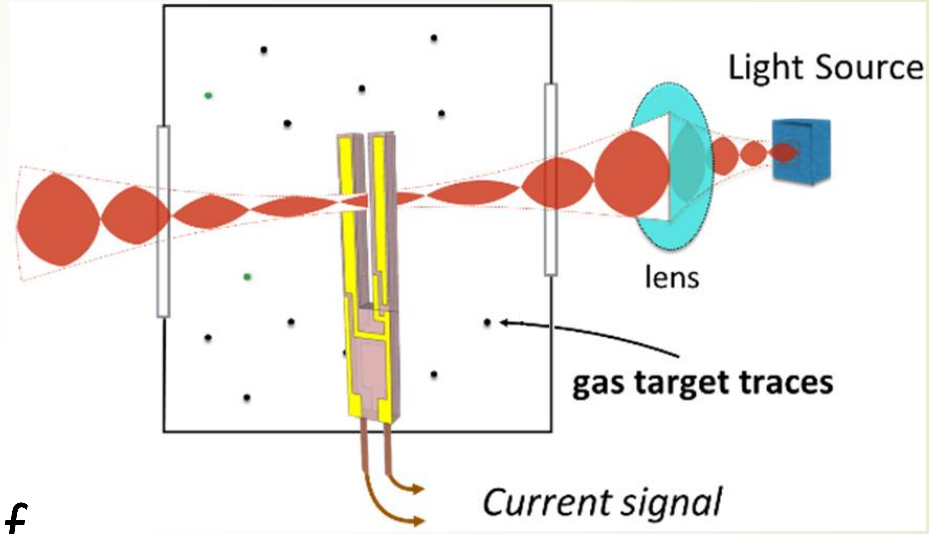
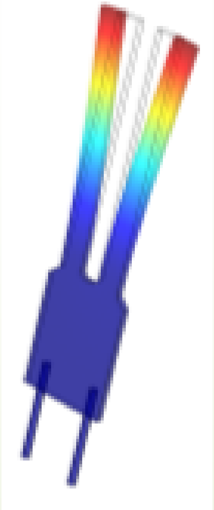


$$S = CP\alpha Q \qquad Q = f/\Delta f$$

Main advantages

- High-Q element
- Narrow spectral passband
- Antisymmetric vibration inactive
- Gas samples volume of ~ *1 mm*^{3}



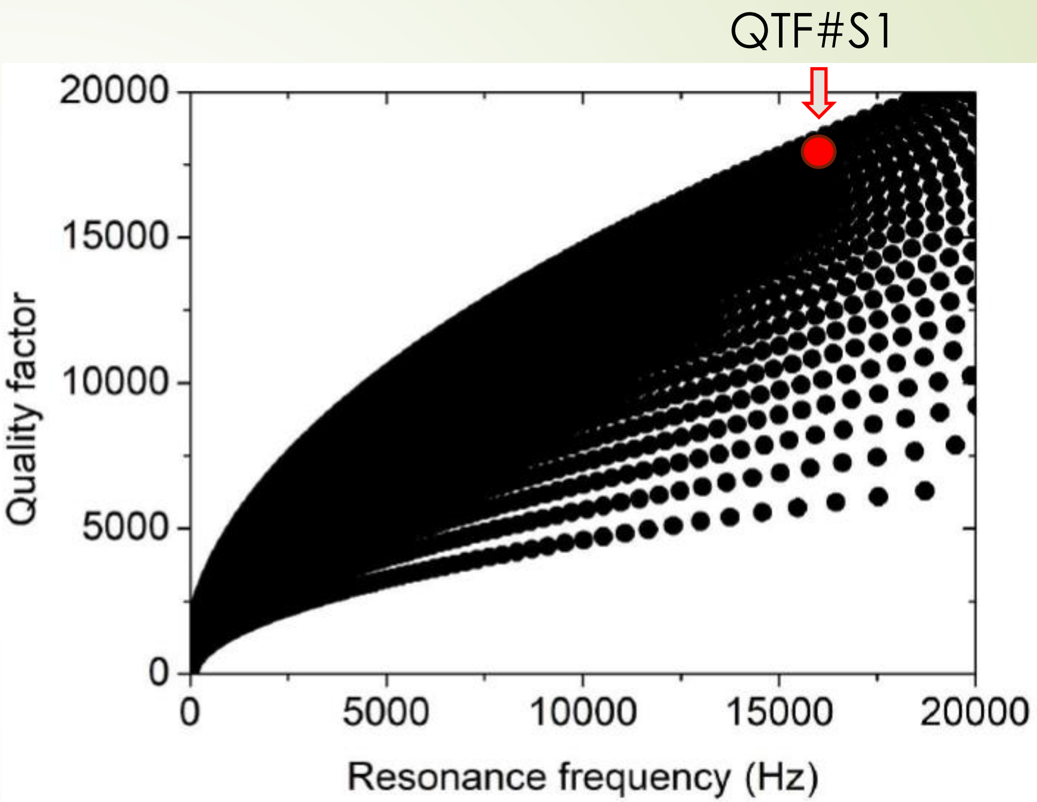
Standard QTF
$f = 32.7$ kHz
$Q_{ATM} \sim 10000$

$$\mathbf{f < 1/2\pi\tau}$$

Custom quartz tuning forks design

Low resonance frequency $f_0 \propto \frac{T}{{L_p}^2}$

High Quality factor $Q \propto \frac{Tw}{L_p}$



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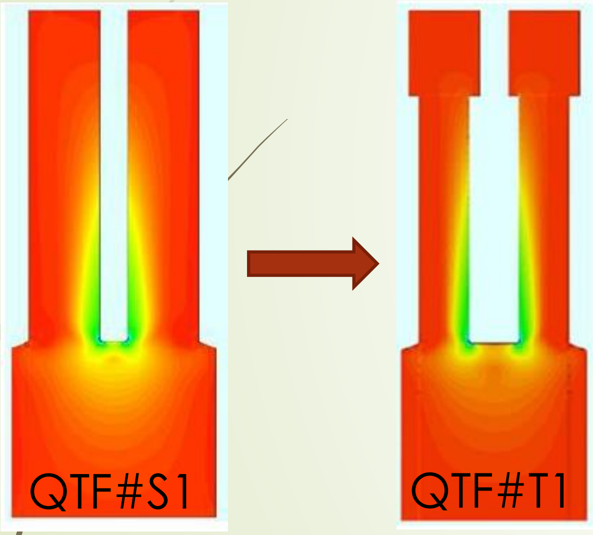
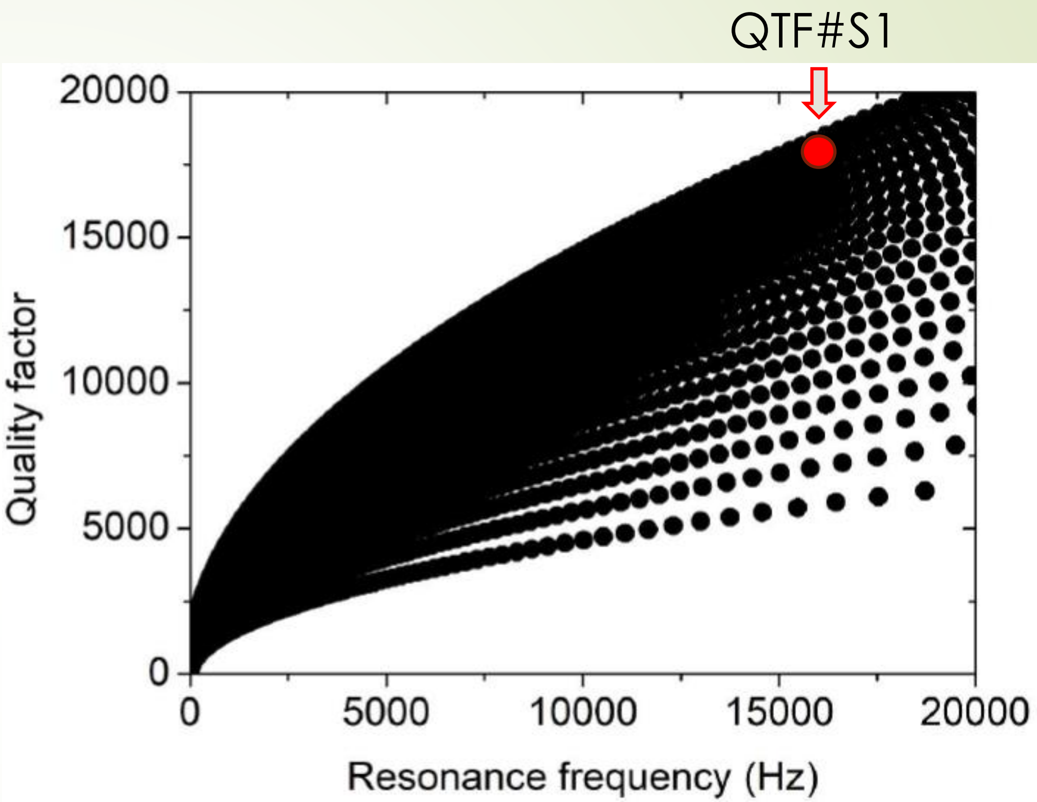


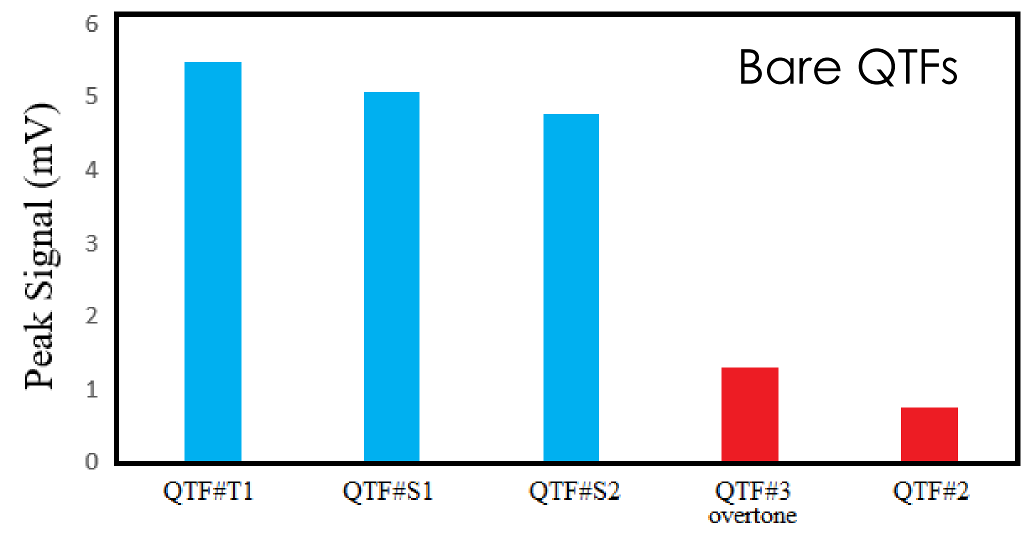
T-shaped QTF

Low f
High Q



QTF	Frequency (Hz)	Q-factor
QTF#S1	15842	15710
QTF#T1	12463	15260

Custom T-shaped QTF performance



- 2nd generation QTFs
- Best results of 1st generation QTFs

P. Patimisco, A. Sampaolo, M. Giglio, **S. Dello Russo,** V. Mackowiak, H. Rossmadl, A. Cable, F.K. Tittel, V. Spagnolo, "Tuning forks with optimized geometries for quartz-enhanced photoacoustic spectroscopy", Opt. Express **2019**, 27, 1401–1415

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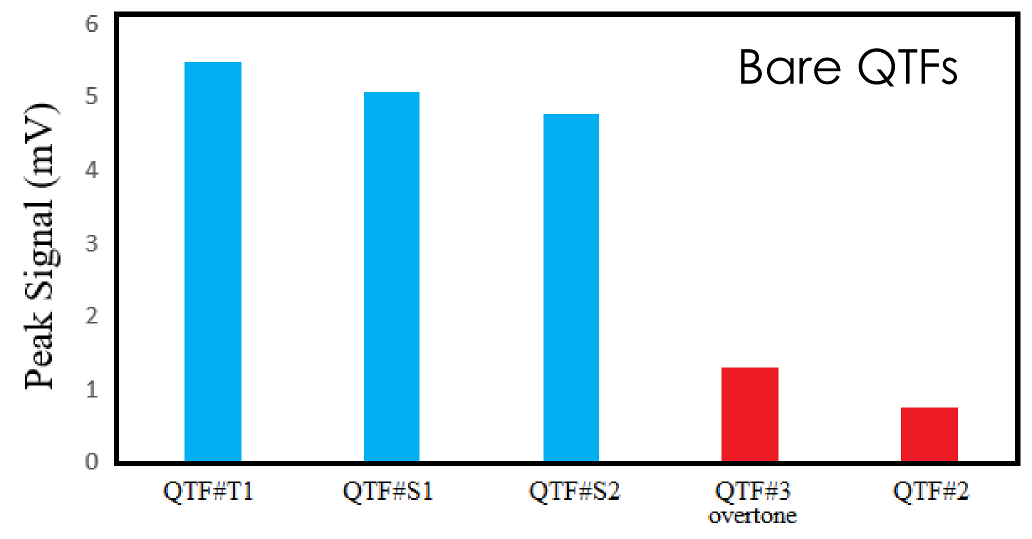

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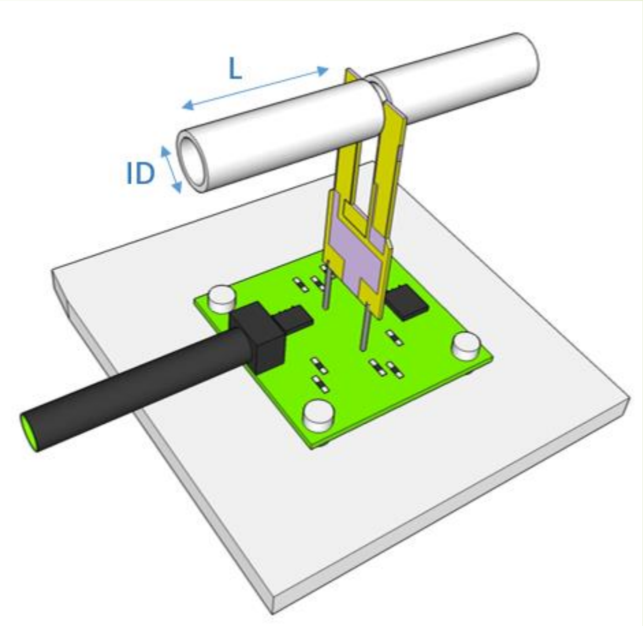
QTF – AmR coupling study



	SNR enhancement
I-shaped + AmR tubes	28
T-shaped + AmR tubes	**60**

Record value for
- MID-IR spectral range
- Dual-Tube configuration

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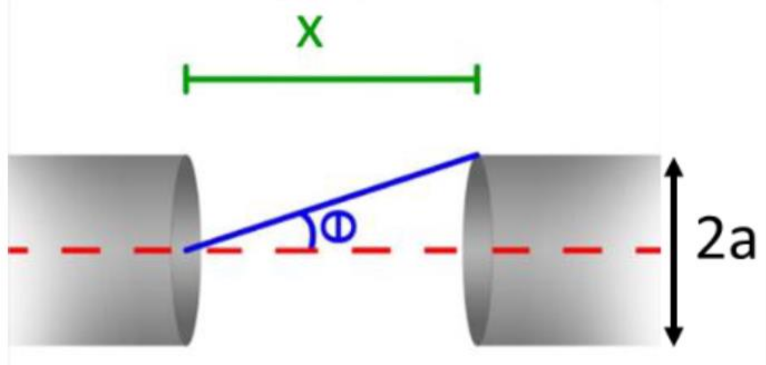
QTF – AmR coupling analysis

Power-gain function

$$G(ka,\theta) = \frac{4}{\pi sin^2\theta}\frac{J_1(kasin\theta)}{\sqrt{J_1(kasin\theta)^2 + [N_1(kasin\theta)]^2}}\frac{|R|}{1-|R|^2}exp\left\{\frac{2kacos\theta}{\pi}P\int_0^{ka}\frac{xtan^{-1}\left[-\frac{J_1(x)}{N_1(x)}\right]}{\left[x^2-(kasin\theta)^2\right]\sqrt{\left[x^2+(ka)^2\right]}}dx\right\}$$



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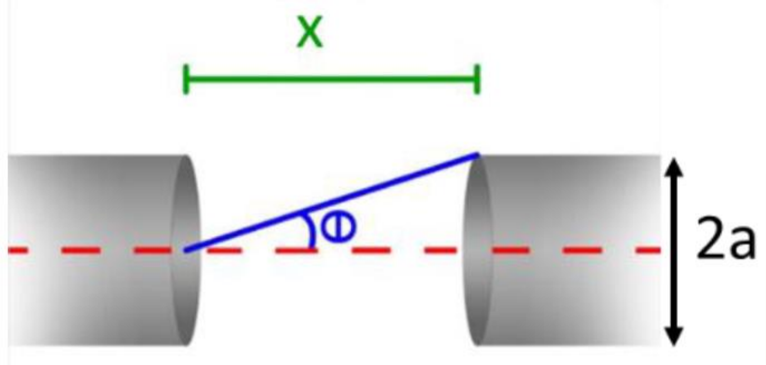
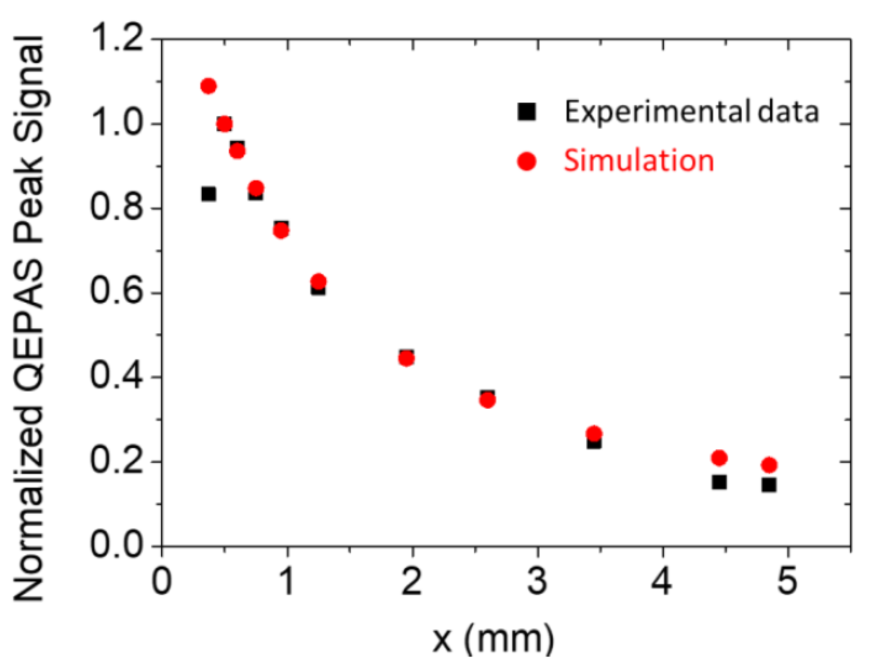


$$C(ka)=2\int_0^{\theta(a)}G(ka,\theta)d\theta$$



QTF – AmR coupling analysis

The antinode appears a little out from the end of the tube and forms the ***Open End Correction (OEC).***

$$L_{th} = \frac{v_{SOUND}}{2f_0} - \frac{8ID}{3\pi}$$

S. Dello Russo, M. Giglio, A. Sampaolo, P. Patimisco, G. Menduni, H. Wu, L. Dong, V.M.N Passaro, V. Spagnolo, "Acoustic Coupling between Resonator Tubes in Quartz-Enhanced Photoacoustic Spectrophones Employing a Large Prong Spacing Tuning Fork", Sensors **2019**, *19*(19), 4109

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QTF	Prong Spacing (mm)	ID (mm)	λ/2 (mm)	L_{th} (mm)	L_{exp} (mm)	QEPAS SNR Enhancement
Standard	0.3	0.6	5.25	4.73	4.4	30
QTF#2	0.8	1.3	23.89	22.79	23	40
QTF#4	1	1.52	6.76	5.47	5.3	15
QTF#T1	0.8	1.59	13.79	12.43	12.4	60

The theoretical model predicts very well the optimal tube length for a tube ID

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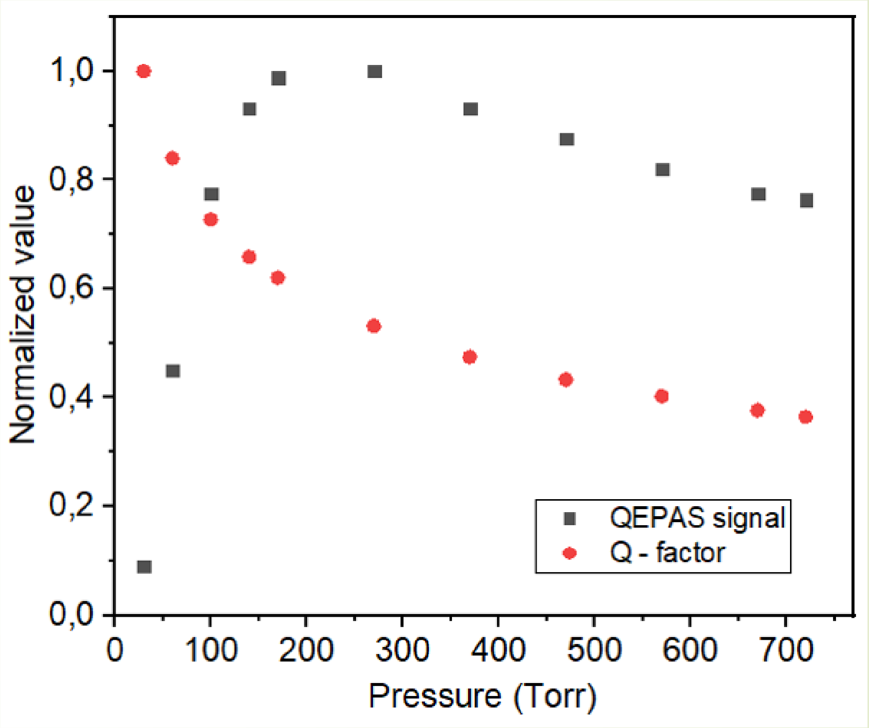
Relaxation rates measurements

$$S(p) = K_{st} P_L C_{gas} Q(p) \varepsilon(p)$$

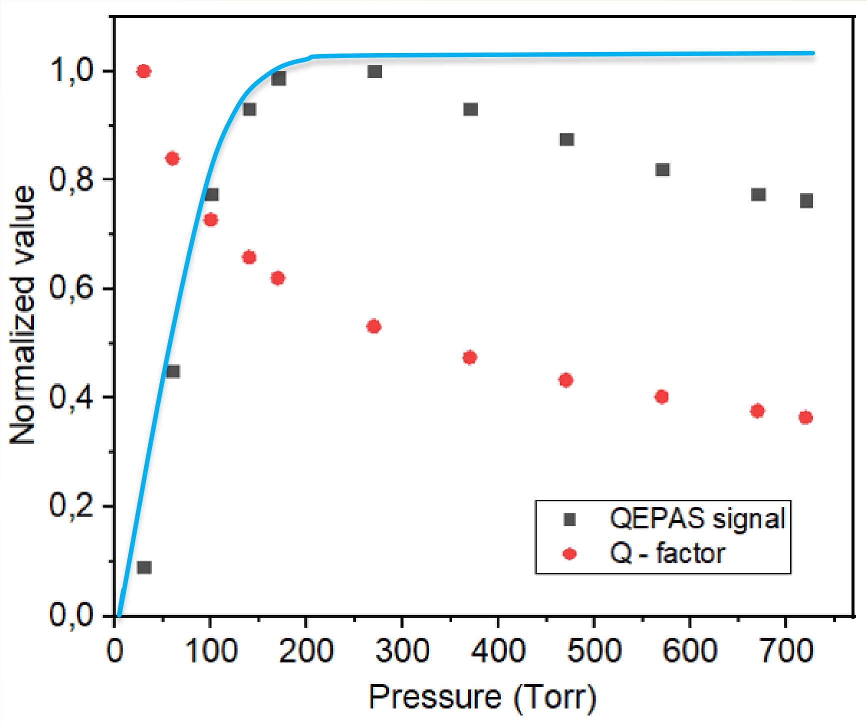


- Decrease of the quality factor Q(p) with increasing pressure due to the increase in viscosity of the surrounding medium

Relaxation rates measurements

$$S(p) = K_{st} P_L C_{gas} Q(p) \varepsilon(p)$$

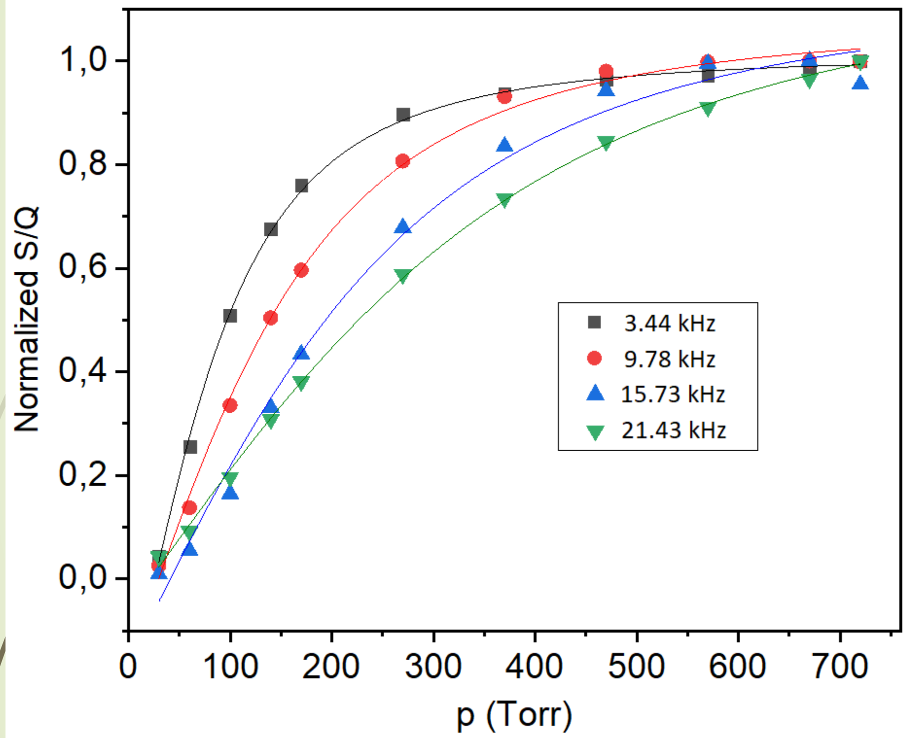
$$\varepsilon(\mathrm{p}) = \frac{1}{\sqrt{1 + \frac{(2\pi f p_0 \tau_0)^2}{p^2}}}$$



- Decrease of the quality factor Q(p) with increasing pressure due to the increase in viscosity of the surrounding medium
- Increase of the radiation-to-sound conversion efficiency (RtSe) $\varepsilon(\mathrm{p})$ towards higher pressures, due to the increased rate of molecular collisions and hence a faster V–T relaxation.

Relaxation rates measurements

Ratio between measured QEPAS peak signal and QTF quality factor for a set of custom QTFs



Results obtained with CH_4
Mixture: 1% CH_4 - 0.15% H_2O - 98.85% N_2

Manuscript under preparation

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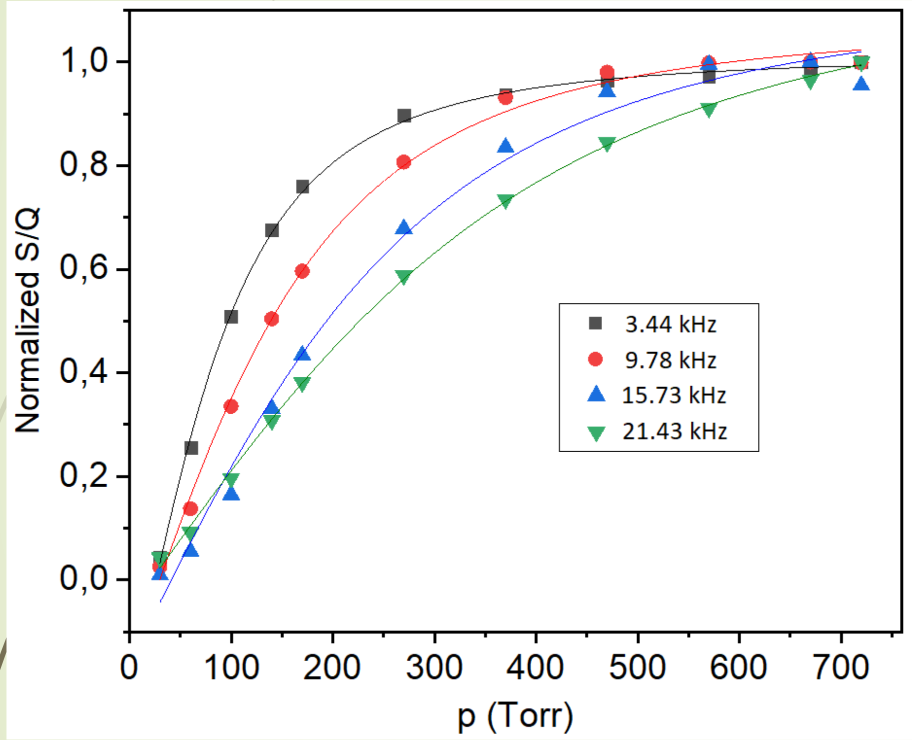

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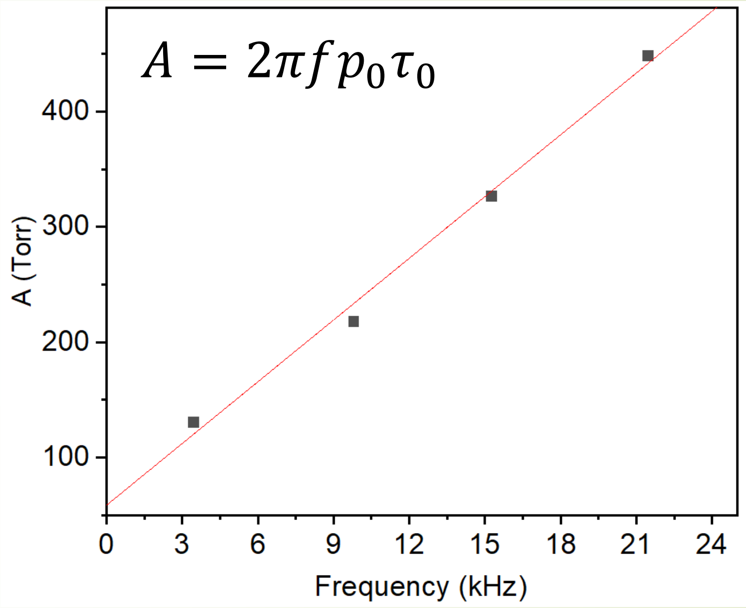


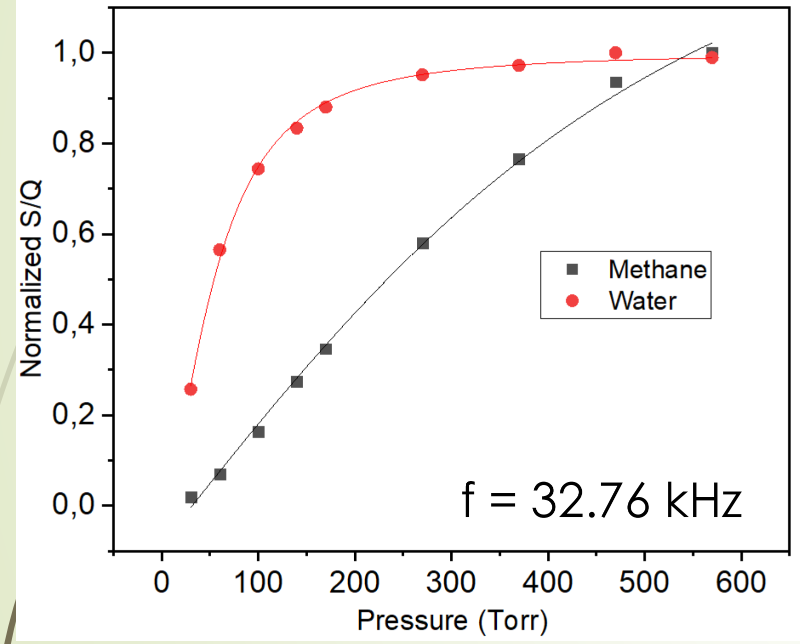
$$\tau_M^{-1} = \sum_i C_i \tau_{M-M_i}^{-1}$$

Expected value: $p_0\tau_0$ = 3.2 ms·Torr
Measured value: $p_0\tau_0$ = 3.3 ± 0.1 ms·Torr

Manuscript under preparation

QTF performance comparison

The slow-relaxer/fast-relaxer signal ratios allows to eliminate the contributions due to the tuning fork, such as the quality factor and the instrumental constants.



Strong dependence on different relaxation rates

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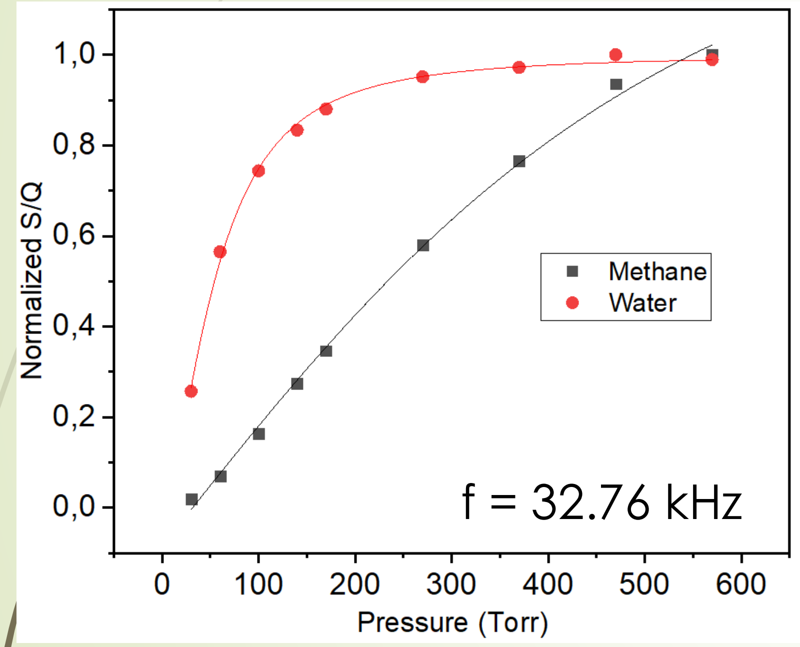

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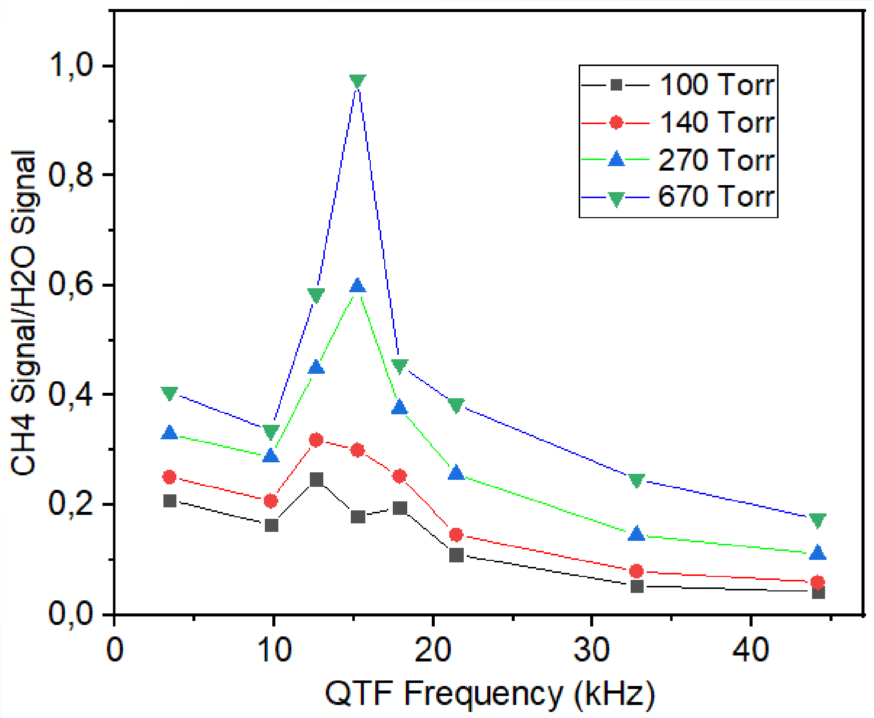
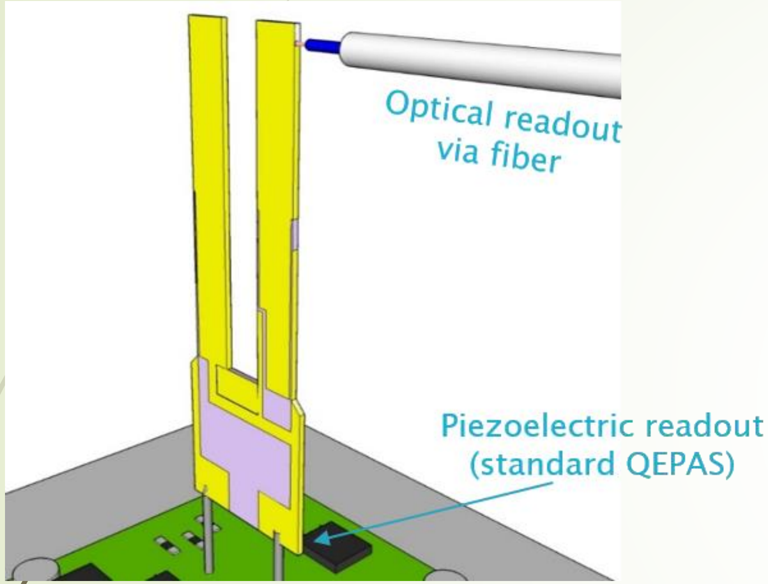


Behavior due to the optimal matching between resonance frequency and relaxation rate

Manuscript under preparation

Interferometric PAS with custom QTFs

For applications in which electromagnetic field may distort the piezoelectric signal



The QTF can be properly designed to enhance one readout with respect to the other one

S. Dello Russo, S. Zhou, A. Zifarelli, P. Patimisco, A. Sampaolo, M. Giglio, D. Iannuzzi, V. Spagnolo, "Photoacoustic spectroscopy for gas sensing: a comparison between piezoelectric and interferometric readout in custom quartz tuning forks", **submitted**

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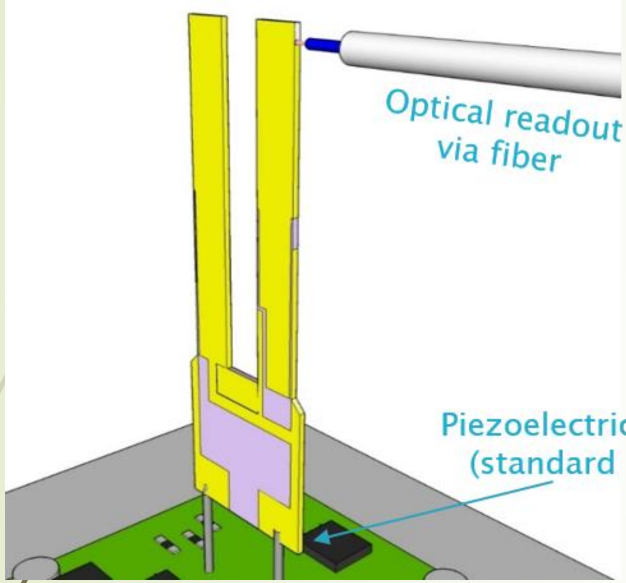

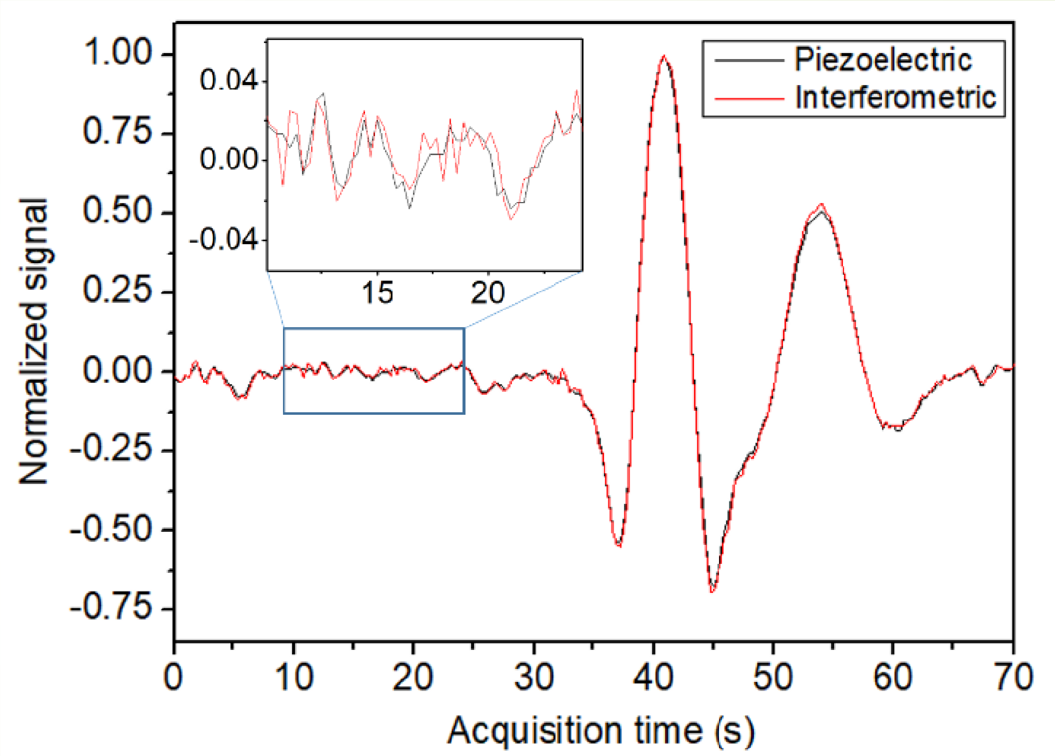

The QTF can be properly designed to enhance one readout with respect to the other one

	T-QTF	1st gen QTF
Piezoelectric readout (SNR)	**84**	23
Optical readout (SNR)	60	**35**

S. Dello Russo, S. Zhou, A. Zifarelli, P. Patimisco, A. Sampaolo, M. Giglio, D. Iannuzzi, V. Spagnolo, "Photoacoustic spectroscopy for gas sensing: a comparison between piezoelectric and interferometric readout in custom quartz tuning forks", **submitted**

Second year goals

- Light induced thermo-elastic spectroscopy

  Corrosive gas sensing
  Gas matrix influence avoided

- QEPAS for wide range gas target concentration

  From gas traces to high concentrations sensing
  Investigation of non-linearities

List of attended courses (14 CFU)

- Promozione della ricerca scientifica (Prof. De Gennaro)
- How to prepare a technical speech in English (Prof. White)
- Programming with Python for Data Science (Prof. Diacono)
- Atom-photon interactions (Prof. Pepe)
- Optical sensors and spectroscopic techniques (Prof. Patimisco)
- Applications of MATLAB (Prof. Dotoli)
- Introduction to C++ programming (Prof. Cafagna)

- Exam passed
- Course attended

List of publications

- P. Patimisco, A. Sampaolo, M. Giglio, **S. Dello Russo,** V. Mackowiak, H. Rossmadl, A. Cable, F.K. Tittel, V. Spagnolo, “Tuning forks with optimized geometries for quartz-enhanced photoacoustic spectroscopy”, Opt. Express **2019**, 27, 1401–1415.
- **S. Dello Russo,** M. Giglio, A. Sampaolo, P. Patimisco, G. Menduni, H. Wu, L. Dong, V.M.N Passaro, V. Spagnolo, “Acoustic Coupling between Resonator Tubes in Quartz-Enhanced Photoacoustic Spectrophones Employing a Large Prong Spacing Tuning Fork”, Sensors **2019**, *19*(19), 4109.
- **S. Dello Russo**, S. Zhou, A. Zifarelli, P. Patimisco, A. Sampaolo, M. Giglio, D. Iannuzzi, V. Spagnolo, “Photoacoustic spectroscopy for gas sensing: a comparison between piezoelectric and interferometric readout in custom quartz tuning forks”, Photoacoustics, **submitted.**

Conference proceedings

- **S. Dello Russo**, P. Patimisco, A. Sampaolo, M. Giglio, G. Menduni, A. Elefante, V.M.N. Passaro, F.K. Tittel, V. Spagnolo, “Measurement of non-radiative gas molecules relaxation rates by using quartz-enhanced photoacoustic spectroscopy”, Proc. SPIE, Quantum Sensing and Nano Electronics and Photonics XVII, **2020**, **accepted.**
- P. Patimisco, S. Zhou, **S. Dello Russo**, A. Zifarelli, A. Sampaolo, M. Giglio, H. Rossmadl, V. Mackowiak, A. Cable, D. Iannuzzi, V. Spagnolo, “Comparison between interferometric and piezoelectric readout of tuning fork vibrations in quartz-enhanced photoacoustic spectroscopy”, Proc. SPIE, Quantum Sensing and Nano Electronics and Photonics XVII, **2020**, accepted.
- P. Patimisco, A. Sampaolo, M. Giglio, **S. Dello Russo**, A. Elefante, G. Menduni, V.M.N. Passaro, H. Rossmadl, V. Mackowiak, B. Gross, A. Cable, F. K. Tittel, and V. Spagnolo "New generation of tuning forks for quartz-enhanced photoacoustic spectroscopy", Proc. SPIE 10926, Quantum Sensing and Nano Electronics and Photonics XVI, 109260D, **2019**.
- P. Patimisco, A. Sampaolo, M.Giglio, **S. Dello Russo**, A. Zifarelli, G. Menduni, F. Sgobba, A. Elefante, H. Wu, L. Dong, F.K. Tittel, V. Spagnolo, “Trace Gas Detection with Quartz-enhanced Photoacoustic Spectroscopy for Real World Applications”, Proceedings of PIERS **2019** in Rome.
- P. Patimisco, V. Spagnolo, A. Sampaolo, **S. Dello Russo,** M. Giglio, L. Dong, F.K. Tittel, “Improvements In Quartz-Enhanced Photoacoustic Spectroscopy By Employing Optimized Tuning Forks”, Proceedings of ICMAT **2019**, 190653.

Thank you for your attention