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Porous and high temperature piezomaterials for energy harvesting

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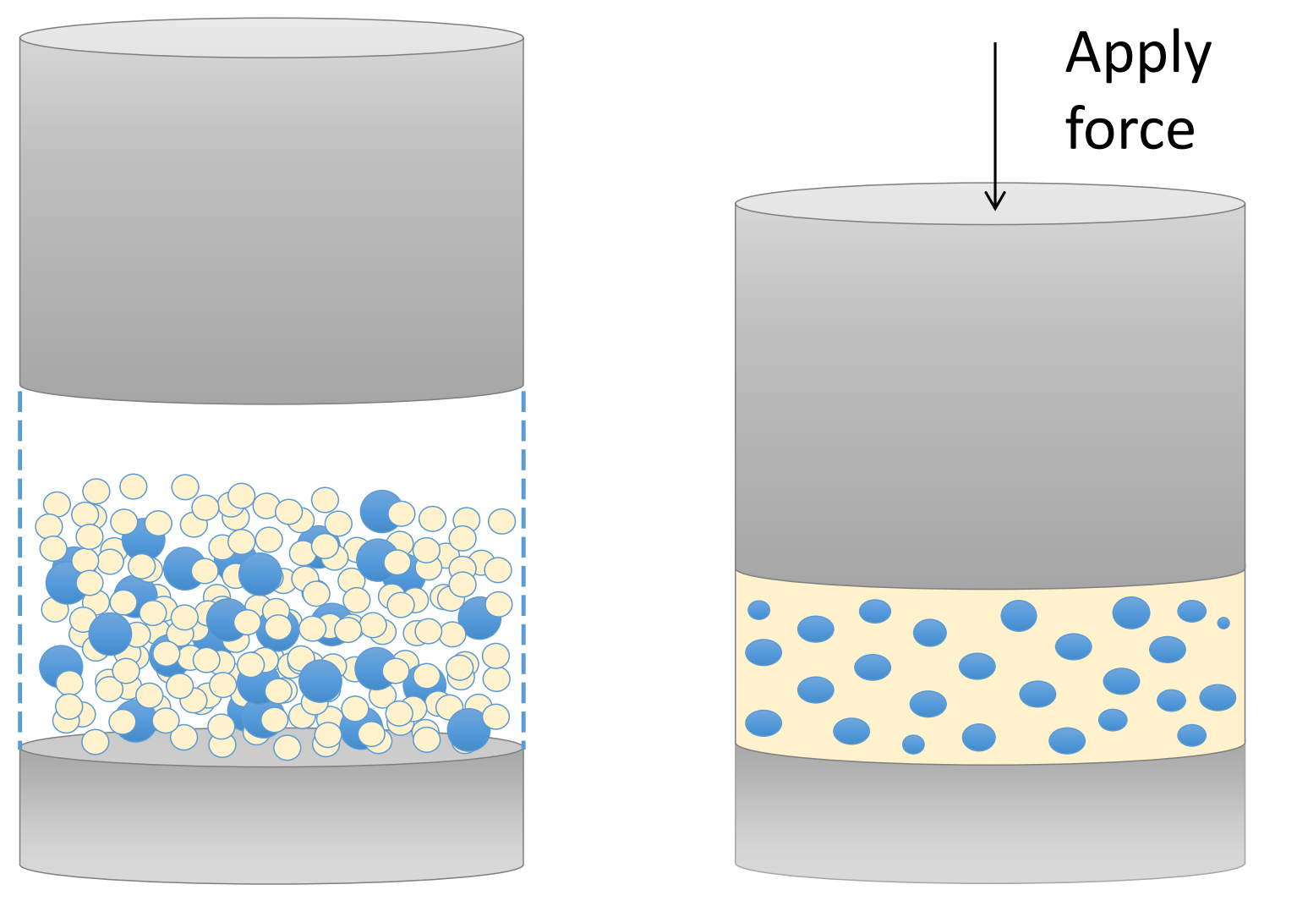
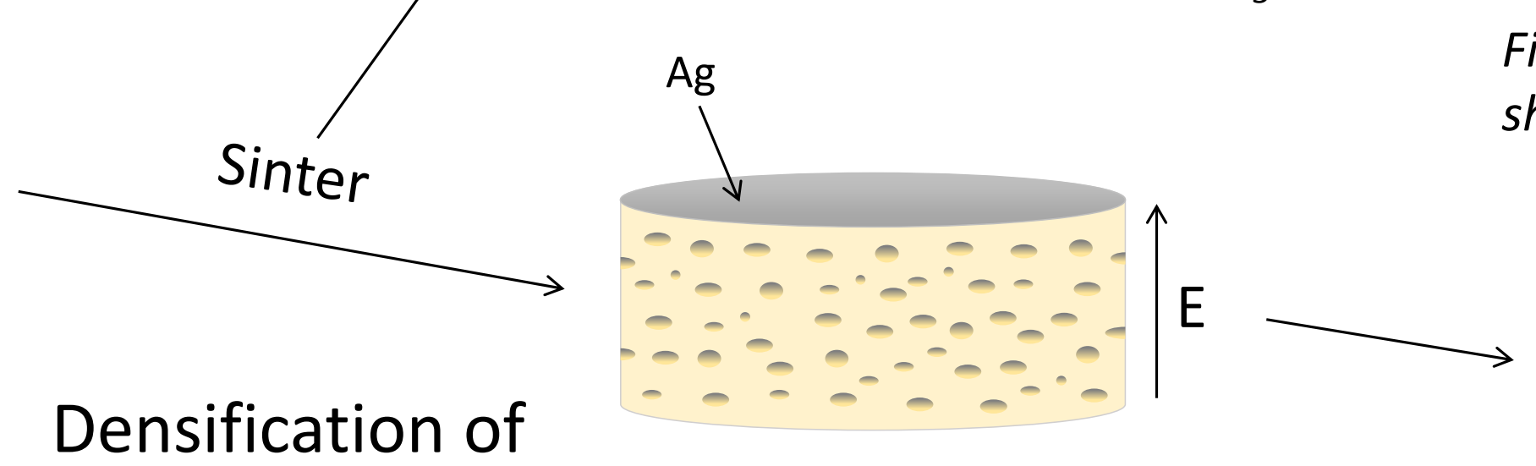
Introduction

The ability to deliver sustainable power to a wireless system network by energy harvesting is attractive not only because of the cost of batteries; it also removes the additional time and cost that is necessary to replace and maintain the batteries and the labour required to install complex wired systems. This is particularly relevant to the installation of sensor networks in areas that are either inhospitable or difficult to reach; this includes safety-monitoring devices and structure-embedded micro-sensors. While the energy harvesting technologies are continuously improving there are also similar advances in microprocessor technology leading to an increase in power efficiency and reduced power consumption. Local electrical energy storage solutions are also improving, i.e. the development of super-capacitors. This convergence of technologies will ultimately lead to successful energy harvesting products and systems.

Context

Ferroelectric ceramics, such as barium titanate and PZT, have the ability to maintain a spontaneous polarisation leading to both piezoelectric and pyroelectric behaviour, making them of particular interest for energy harvesting applications. Introducing porosity to form ceramic-air piezocomposites yields beneficial properties for SONAR applications [1] and it is thought the same principles can be applied to energy harvesting. Piezoceramics can be characterised by an energy harvesting figure of merit (FOM) [2], $d_{33}^2/\varepsilon_{33}^{\sigma}$, where d_{33} is the longitudinal piezoelectric coefficient and $\varepsilon_{33}^{\sigma}$ is the permittivity at constant stress. This work aims to demonstrate that introducing high levels of porosity can yield an improvement in FOM due to a significant reduction in permittivity.

Method – Porous $BaTiO_3$ made via BURPS (Burned-out Polymer Spheres) process

Milled $BaTiO_3$ powder mixed with pore forming agent (PFA) in varying wt%

Powders uniaxially pressed to form green pellets

Densification of ceramic phase, burn out of PFA

Corona poling under electric field, E

Measure piezoelectric and dielectric properties:

- Piezometer PM25 (*Take Control*)
- Solartron 1260 Impedance/Gain Analyzer

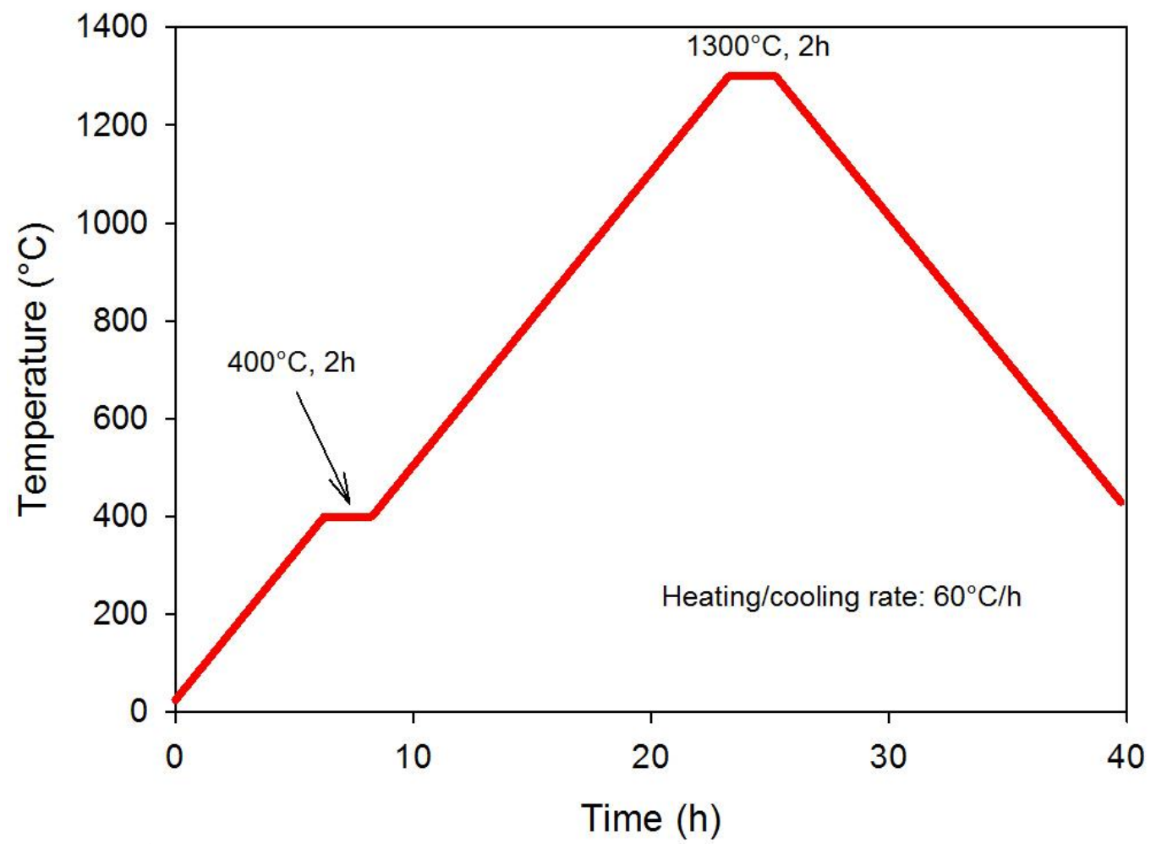


Fig 1: Sintering profile for $BaTiO_3$

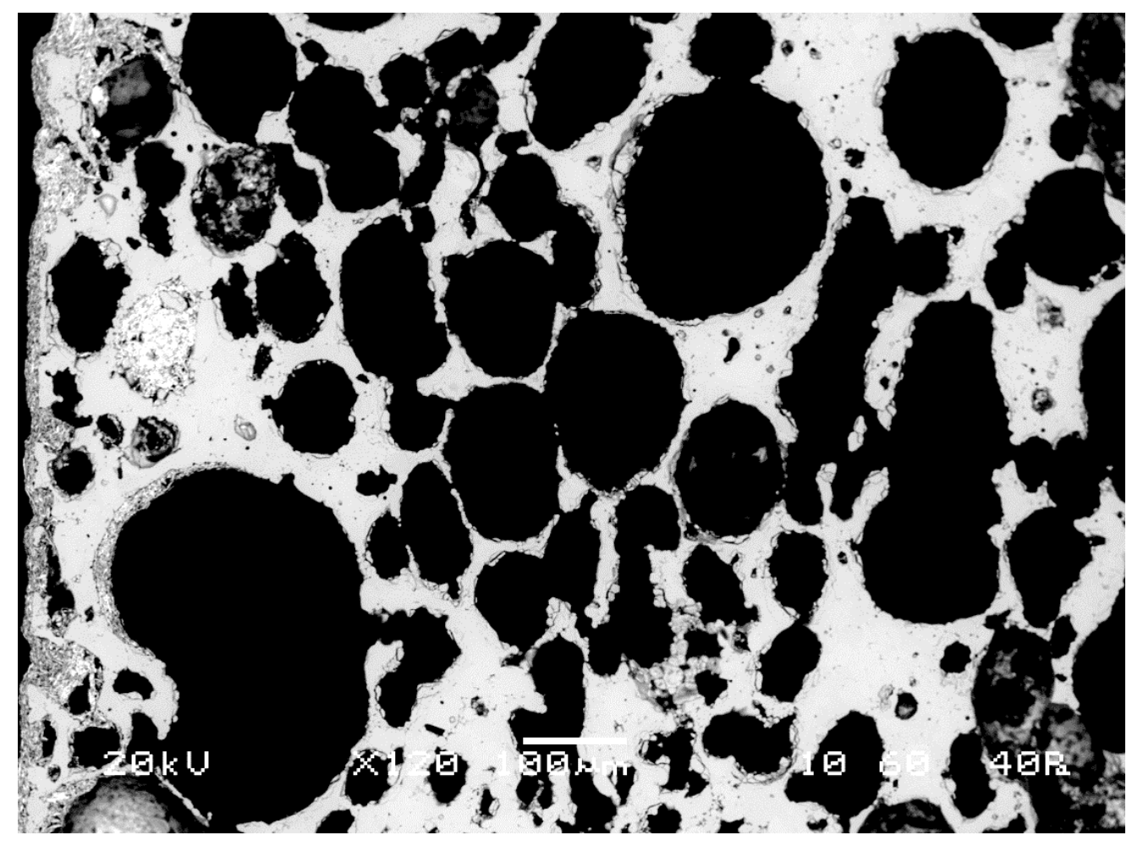


Fig 2: SEM image of 60% porous barium titanate showing macroporous structure with 3-3 connectivity

Results

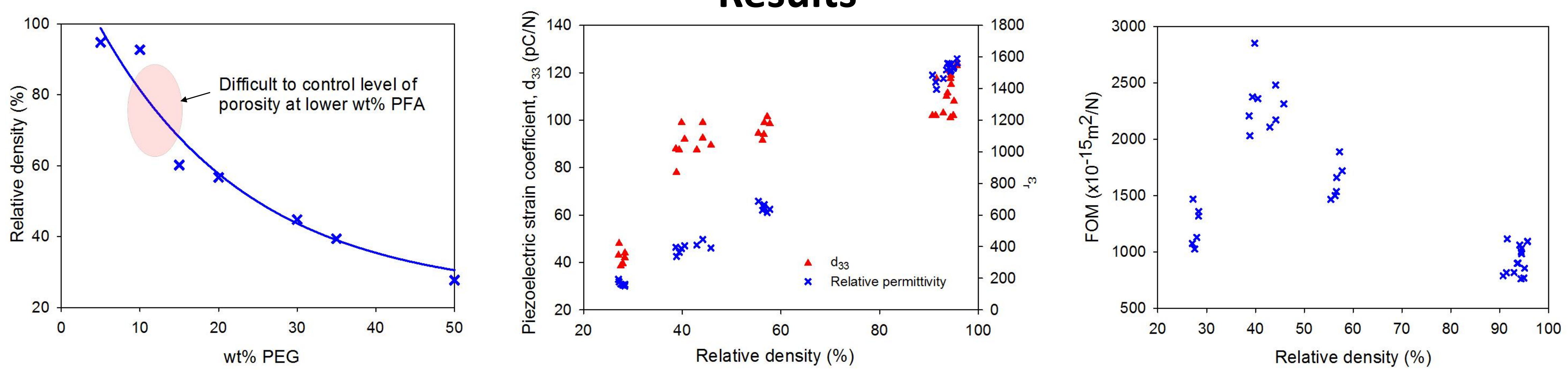


Fig 3: a) Variation in post-sinter relative density with wt% pore former, b) piezoelectric strain coefficient and relative permittivity (at 1kHz) of BaTiO3 as a function of porosity and c) energy harvesting FOM as a function of porosity

- Reducing relative density through introduction of porosity results in significant decrease in permittivity for relatively small reduction in d_{33}
- FOM increases up to ~60% porosity – drop off due to difficulty in poling high porosity ceramics because of electrical breakdown

Discussion and outlook

- Initial results indicate there is potential for porous ferroelectrics in piezoelectric energy harvesting due to increase in FOM with increasing porosity
- However, porosity reduces the stiffness of the material – linked to electromechanical coupling coefficient, k_{33}^2, and therefore the efficiency of conversion
    - Limitation of 3-3 structure – other structures may exhibit improved mechanical properties whilst maintaining benefits of porosity in terms of FOMs
- Investigate alternative processing routes in order to obtain different structures.

References

[1] Newnham, R. E., Skinner, D. P., & Cross, L. E. (1978). Connectivity and piezoelectric-pyroelectric composites. *Materials Research Bulletin*, *13*, 525–536.
[2] Islam, R. A., & Priya, S. (2006). Realization of high-energy density polycrystalline piezoelectric ceramics. *Applied Physics Letters*, *88*(3), 032903.

Context

There has been increasing interest in development of high temperature energy harvesters for applications such as near-engine sensors and remote sensors for geothermal explorations (>600°C). However the common piezo materials considered for vibration energy harvesters such as lead zirconate titatate (PZT) piezoceramics are unsuitable as the typical operating range is below 400°C.

Purpose of the work

The aim of this study was not to optimize the design of the harvester but to assess the potentiality of $LiNbO_3$ single crystal Y-cut (010) oriented for high temperature energy harvesting. The degradation of LiNbO3 is assessed via impedance spectroscopy measurements from RT to 750°C back to RT. Output voltage and harvested power as a function of electrical load up to 500°C were recorded. Difficulties and particularities related to the design of high temperature harvester are addressed.

Electrical behaviour of Y-cut $LiNbO_3$ single crystal harvester element with temperature

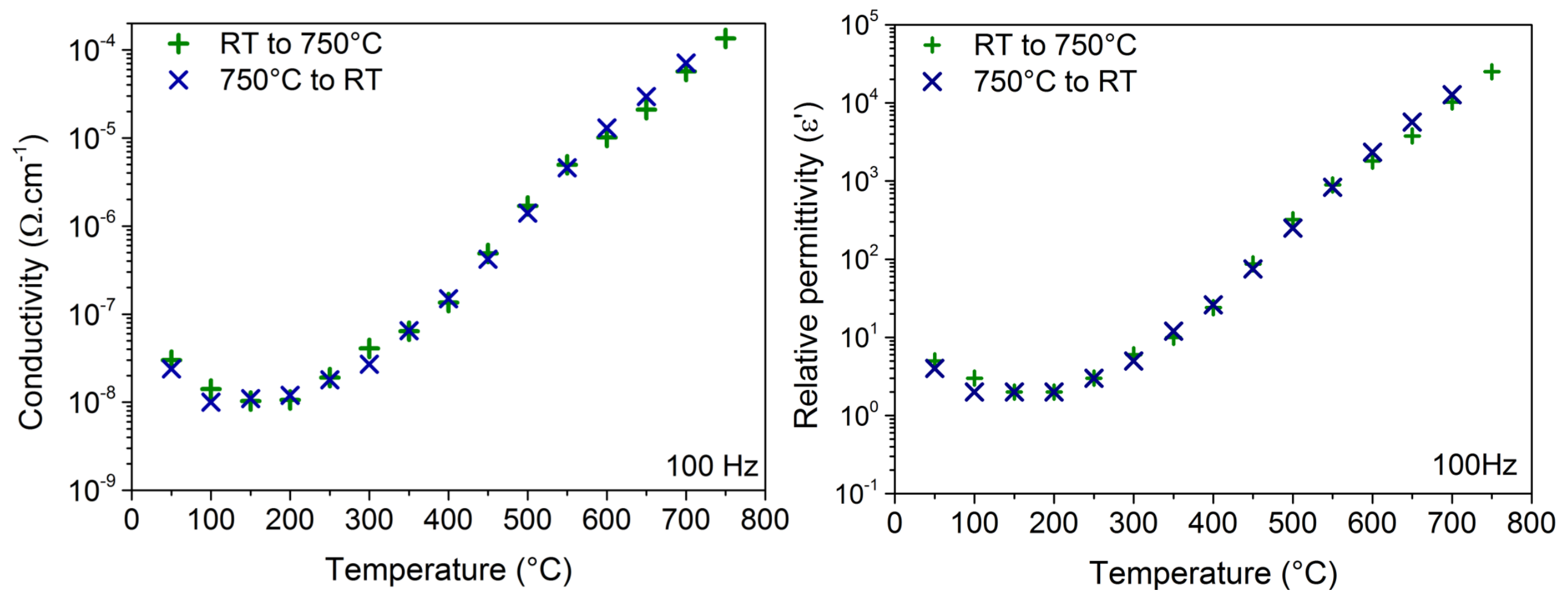


Fig 1: (a) Conductivity and (b) relative permittivity of Y-cut $LiNbO_3$ single crystal as a function of temperature

- Stability of $LiNbO_3$ electrical behaviour from RT to 400°C
- Exponential increase of conductivity and relative permittivity with temperature after 400°C
    - Lower internal resistance
    - Higher dielectric loss
- Lost of the capacitive behaviour of $LiNbO_3$ at higher temperature
- Reversibility of $LiNbO_3$ after exposition to high temperature

Set-up and methods

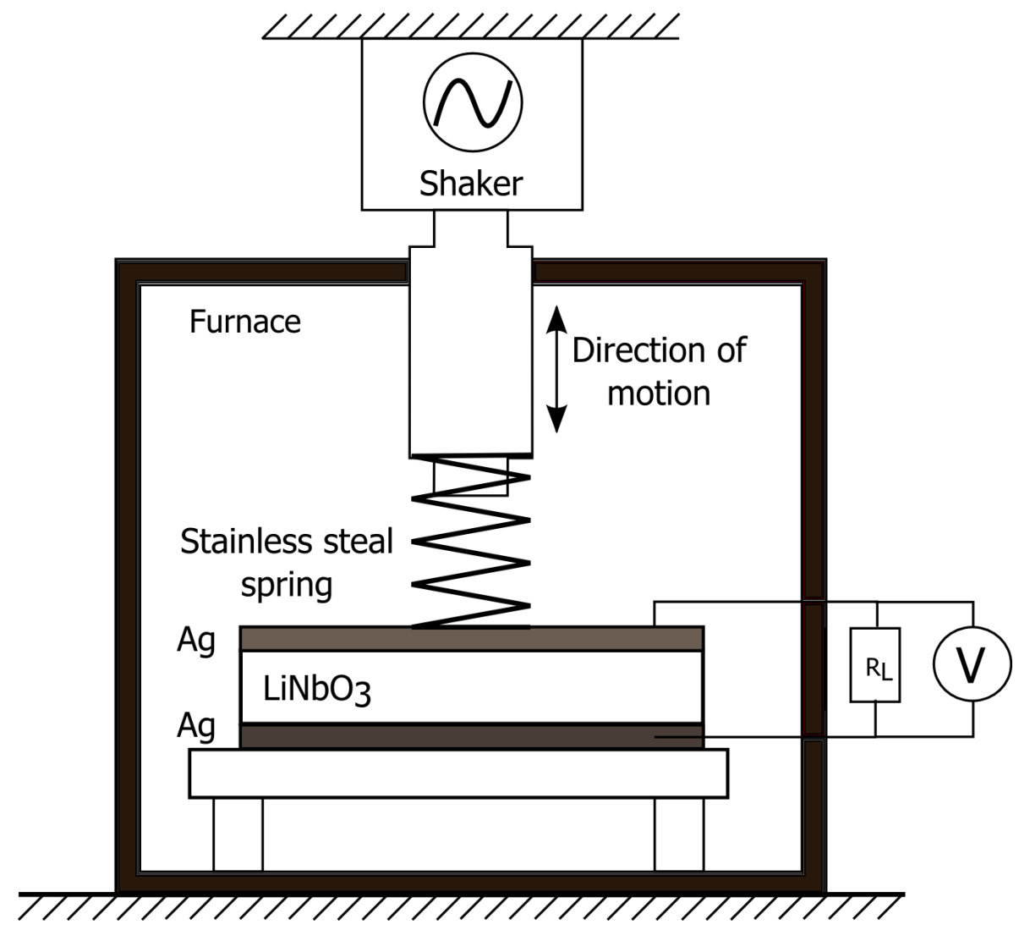


Fig 2: Schematic of the rig set-up for vibration-based energy harvesting at high temperature

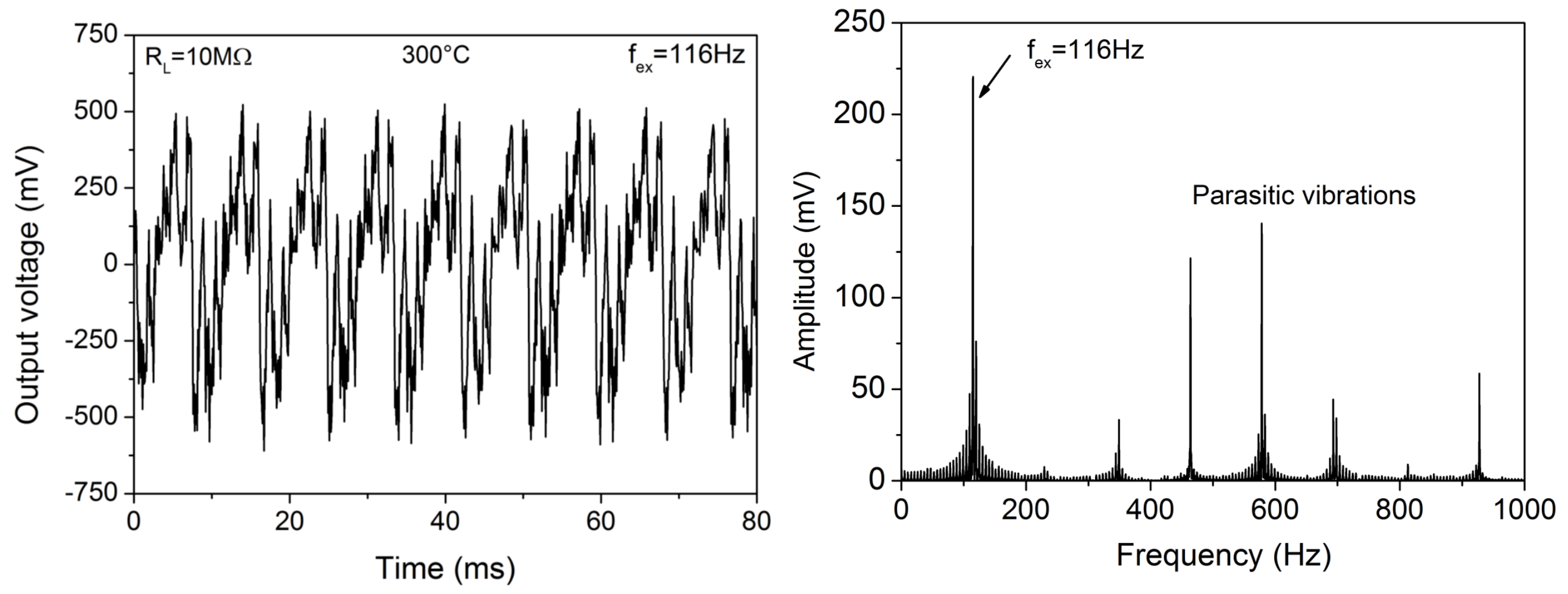


Fig 3: (a) Electrical signal and (b) Fourier transform obtained for $LiNbO_3$ Y-cut single crystal excited at a frequency of 116Hz at 300°C for a load resistance of 10MΩ

Noisy signal due to system parasitic vibrations

Fourier transform

Efficiently remove parasitic vibrations

Accurately isolate and measure output voltage related to the frequency of excitation

Results

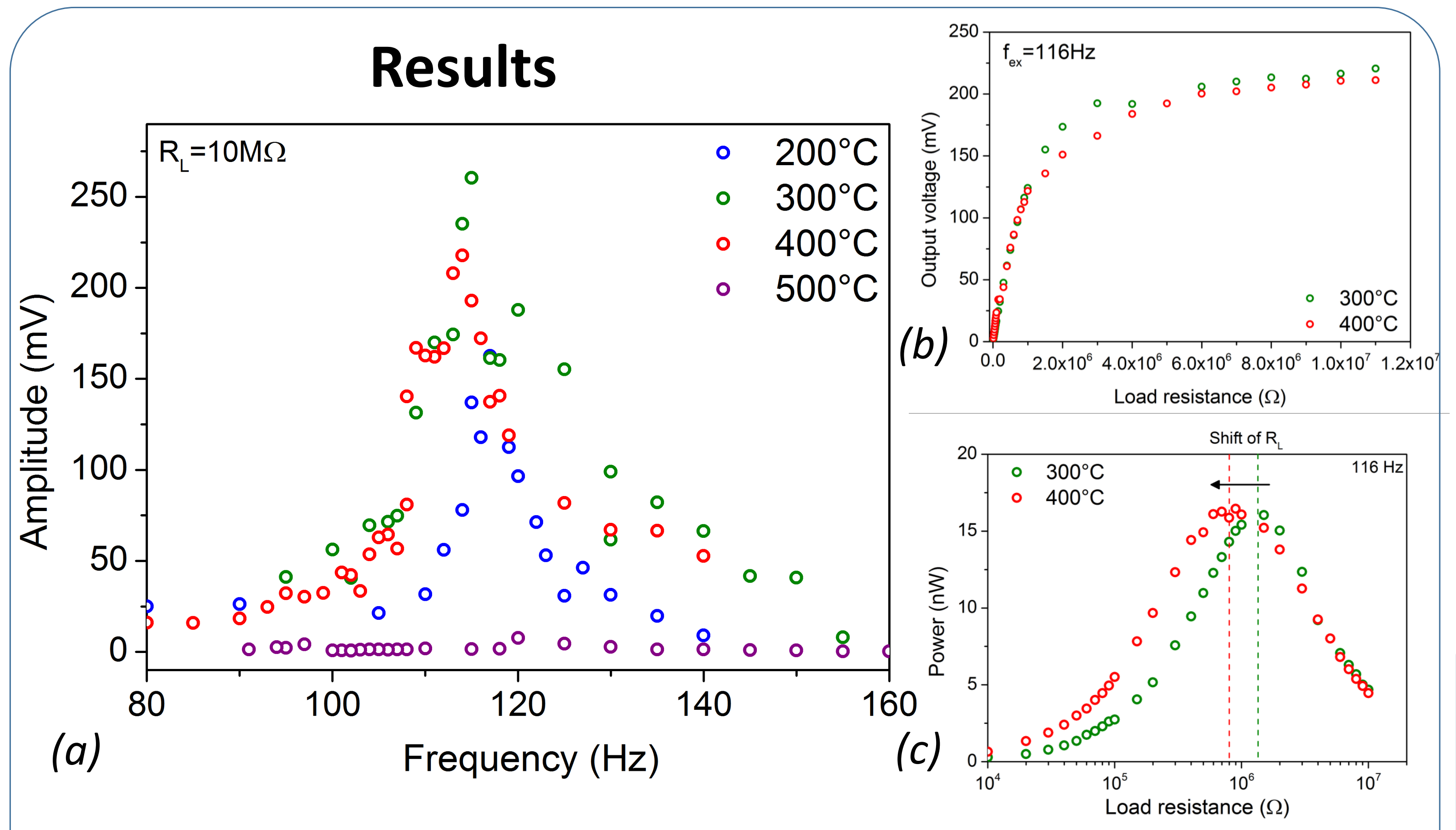


Fig 4: (a) Output voltage as a function of frequency obtained from 200°C to 500°C (b) Output voltage and (c) output power as a function of load resistance at 116Hz for 300°C and 400°C

Conclusions

- Reversibility of $LiNbO_3$
- Demonstrated energy harvesting with $LiNbO_3$ Y-cut single crystal up to 400°C
- Failure of stainless steel spring limited the investigation to 400°C
- Shift in optimum load resistance with temperature

Perspectives

- Change spring material to investigate higher temperature (600°C)
- Investigate other types of materials