Methods for microwave characterization of electro-optic crystals for quantum transduction

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***Abstract*—Microwave-optic quantum transducers are essential to develop distributed quantum networks and implement related quantum communication protocols. Three dimensional high-coherence microwave cavities embedded with electro-optic nonlinear materials provide promising platforms for microwave-optic frequency conversion. However, so far, the properties for such dielectric crystals operating at milli-Kelvin cryogenic temperatures have not been well understood. Here, we propose a scheme to precisely measure the dielectric constant and dissipation mechanisms of electro-optic materials, such as Lithium Niobate, at the quantum threshold. We will use Fermilab's three dimensional superconducting cavities with long coherence time. The proposed method of characterization lays the foundation for engineering quantum transduction devices with high conversion efficiency and high-fidelity.**

***Index Terms*—Quantum, Transduction, Qubit, Coherence, Quantum networks, TLS, Superconducting**

I. Introduction

Superconducting qubits and resonators are leading candidates to build scalable quantum processing units (QPUs), with fast operation gates and long enough coherence times. However, they have to be cooled down to milli-Kelvin temperatures to operate at the single photon level and avoid detrimental thermal noise. High-efficiency microwave-optic quantum transduction devices are essential to develop distributed quantum networks and implement the related communication protocols. Current transduction demonstrations are limited in conversion efficiency, due to the weak interaction between the microwave and optical fields. At Fermilab, we have developed superconducting radio-frequency (SRF) cavities with record-high photon lifetime, up to 2 seconds in the quantum regime [1]. We plan to leverage this technology to realize high-efficiency and low-noise quantum transducers optimized to enhance the conversion efficiency between the microwave and optical fields [2, 3].

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A promising approach for frequency conversion utilizes electro-optic nonlinearity which can be found in noncentrosymmetric crystals such as Lithium Niobate (LiNbO3 or LN) and Aluminum Nitride (AlN). Noncentrosymmetric crystals are widely used in optics for creating second-order nonlinearity for various applications in wave mixing, sideband modulation and signal generation [4]. In particular, with the electro-optic nonlinearity, the microwave signal applied to the crystal modulates the optical refractive index, leading to a three-wave mixing process between the optical pump, the optical signal, and the microwave field. In this way, a bidirectional conversion can be realized between microwave and optical signals. Figure 1 shows the block diagram of a hybrid quantum system (HQS) for microwave-optical quantum transduction, it comprises an SRF cavity coupled to a bulk electro-optic crystal. The crystals behaves as a whispering gallery mode (WGM) optical resonator. The pump excites optical modes of the electro-optic crystal through a prism coupler.

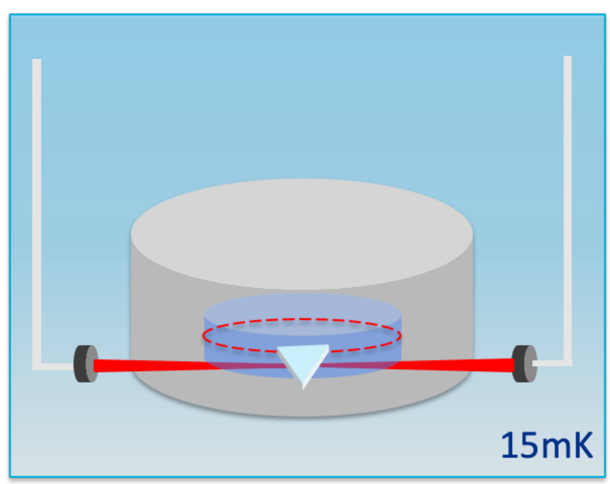


Fig. 1. Block diagram of a hybrid quantum device (HQS) based on bulk SRF and optical cavities for microwave-optical transduction.

The knowledge of the electro-optic and microwave properties of noncentrosymmetric signals at milli-Kelvin temperatures is necessary to accurately design such transducers, understand and mitigate all possible sources of losses, as well as evaluate the conversion efficiency and the fidelity, when coupled to superconducting qubits. This characterization is of particular importance in the design phase to have a correct estimate of the loss tangent and permittivity tensor of the noncentrosymetric crystal enclosed in the microwave cavity.

Electro-optic materials are mostly employed at room or even higher temperatures, while our operation target is in the milli-Kelvin regime. A work from Goryachev et al. have determined the loss tangent of lithium niobate in the order 10^{-5} [5] at the single photon level. Other studies on lithium tantalate [6] and silicon [7] report schemes for microwave characterization, including temperature dependency of loss tangent and permittivity. However, the data available in the literature on these crystals is still very limited.

In this paper, we are presenting methods to carry out full microwave characterization of electro-optic crystals at the quantum threshold. We have designed a high-Q SRF calibration cavity with large mode volume to hold the sample and measure the dielectric permittivity and the loss tangent of such samples with high resolution and with reference to the temperature ($< 1\,\mathrm{K}$).

II. Design of the Cavity and the Characterization System

The system for characterizing electro-optic crystals is based on a cylinder-shape three-dimensional bulk Niobium microwave cavity, which becomes superconducting and exhibits low loss at cryogenic temperature (Fig. 2(a)). Inside the large mode volume, the cavity embeds a nonlinear crystal cubic sample (6x6x6 mm), which is the sample to be characterized. It is supported by a holder made of a dielectric material with negligible loss tangent compared to the sample under test. The holder has one end fixed to the Niobium cavity and the other end fabricated into a concave shape well matching the sample size and thus clamping the crystal (Fig. 2(b)). The cavity is coupled to two variable antenna couplers on the left and right sides of the cavity. The transmission spectrum is measured by sweeping the frequency of the input signal injected to the one port which is weakly coupled to the cavity, and picking up the transmitted signal from the opposite port. The whole setup operates at cryogenic temperatures down to $15\,\mathrm{mK}$.

To ensure a comprehensive measurement of the sample properties, we align the main axis of the sample with the z direction. For materials such as LN, this can be realized by performing z-cut for the crystal. The dielectric constant will take the form of a diagonal matrix, i.e.,

$$\epsilon = \begin{pmatrix} \epsilon_{xx} & 0 & 0 \\ 0 & \epsilon_{yy} & 0 \\ 0 & 0 & \epsilon_{zz} \end{pmatrix} \quad (1)$$

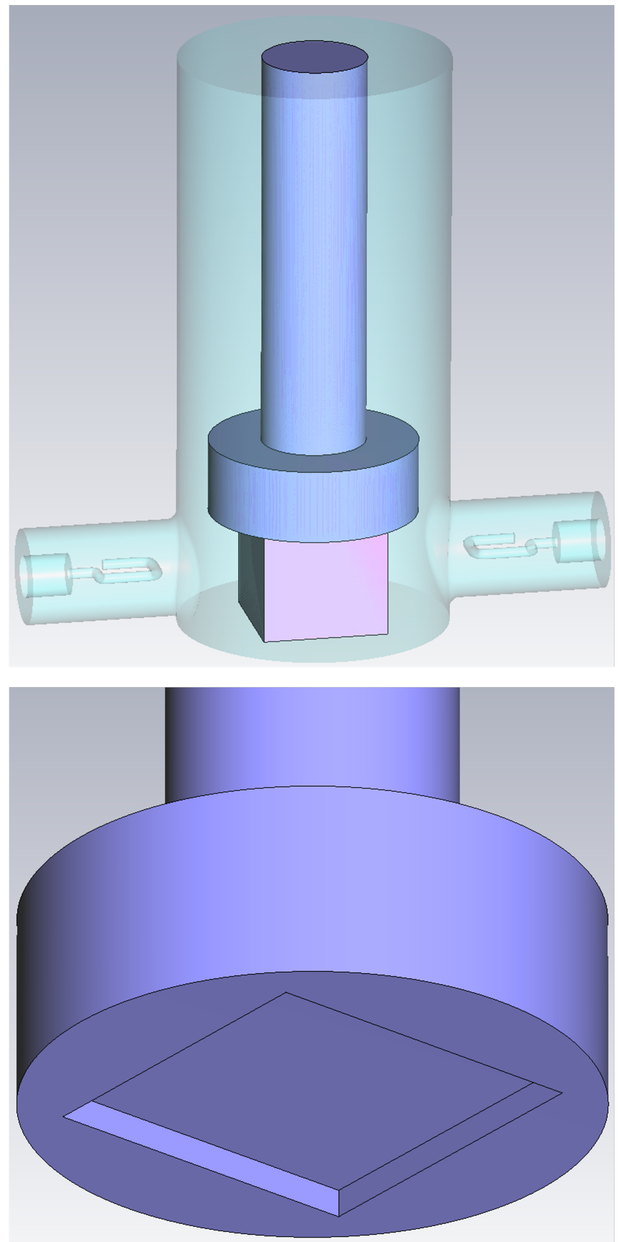
(a)
(b)


Fig. 2. Microwave cavity and system design for electro-optic crystal sample. (a) Schematic diagram for a cubic crystal sample embedded in a three-dimensional microwave cavity system and supported by a low-loss dielectric holder. (b) The closeup of the dielectric holder which fixes the position of the sample to be tested.

III. RF SIMULATIONS OF MICROWAVE MODES

Based on finite-difference-time-domain (FDTD) simulations, we obtain the field distributions of two cavity modes at frequencies $\sim 7\,\mathrm{GHz}$, the electric field distributions are plotted in Fig. 3. The microwave modes of the SRF cavity depend on the dielectric constants of the sample, as is in Table. I. The resonant frequency of the first microwave mode (Fig. 3(a)) shows high dependence on the x and y components of the dielectric constants of the crystals (ϵ_{xx} and ϵ_{yy}), but is almost decoupled from its z component (ϵ_{zz}). For birefringent crystals such as LN for which $\epsilon_{xx} = \epsilon_{yy} \neq \epsilon_{zz}$, the change in ϵ_{xx} and ϵ_{yy} will be well reflected by the resonance frequency shift of the microwave mode. In Fig. 3(b), we show the electric field distribution for another microwave mode, the frequency of which exhibits a strong dependence on ϵ_{zz} but is only weakly affected by ϵ_{xx} and ϵ_{yy}. Such a mode will be used for characterizing the change in ϵ_{zz}.

The quality factor is the one computed with the presence of the crystal in the cavity, which is engineered to be sensitive to the frequency shifts of the microwave mode with reference to the permittivity.

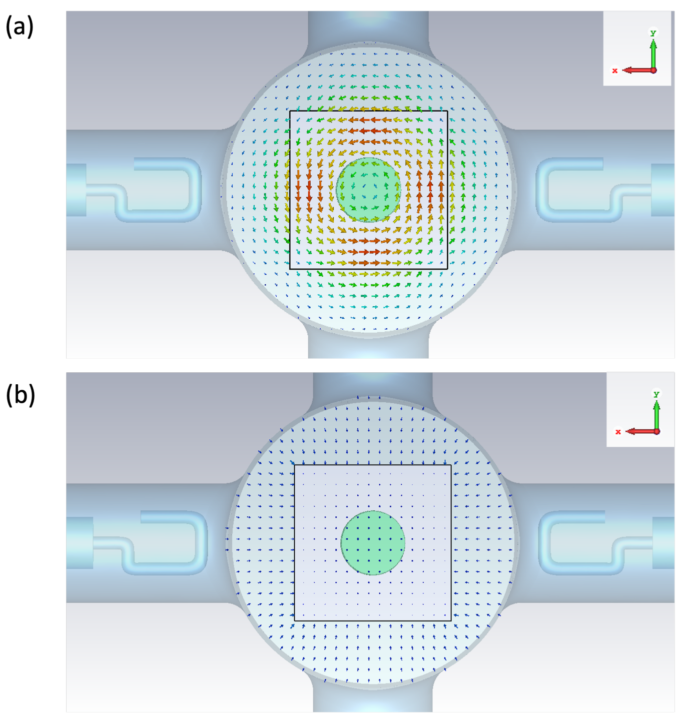


Fig. 3. Microwave cavity design for electro-optic crystal characterization. (a) The electric field distribution for a microwave cavity mode which is only sensitive to $\epsilon_{x,y}$; (b) The electric field distribution for a microwave cavity mode which is only sensitive to ϵ_z.

It is interesting to note that this cavity also supports higher order modes, which, up to $\sim 10\,\mathrm{GHz}$, could also be used for the microwave characterization as well. Moreover, the permittivity tensor can also be evaluated by measuring the different polarizions of dipole modes and the splitting between their frequencies.

TABLE I
DEPENDENCE OF MICROWAVE MODES ON THE COMPONENTS OF THE DIELECTRIC CONSTANT OF THE ELECTRO-OPTIC CRYSTAL SAMPLE AND ESTIMATED QUALITY FACTORS.

Frequency	**Q factor**	$df/d\epsilon_x$	$df/d\epsilon_y$	$df/d\epsilon_z$
7.13 GHz	1.0×10^5	-40.6 MHz	-40.9 MHz	-0.1 MHz
7.58 GHz	2.2×10^5	-0.95 MHz	-0.95 MHz	-60.8 MHz

IV. METHODS OF MEASURING CRYSTAL PROPERTIES

The loaded quality factor (Q_L) of the microwave cavity mode is composed of the internal Q factor (Q_0), coupling Q factors (Q_1 and Q_2), and the dielectric loss on the crystal (Q_d), i.e.

$$\frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_1} + \frac{1}{Q_2} + \frac{1}{Q_d}. \tag{2}$$

Moreover, by including dielectric losses, each element of the dielectric constant of the sample material becomes complex ($\epsilon = \epsilon' + i\epsilon''$), the imaginary part represents the amount of dielectric loss. As the environmental condition (such as temperature or microwave power) varies, the increase/decrease of the dielectric loss on the sample will lead to the change of Q-factor of the microwave modes. We can quantify the amount of microwave losses by the loss tangent ($\tan\delta$) of the sample material, which is given by

$$\tan\delta = \frac{\epsilon''}{\epsilon'}. \tag{3}$$

In particular, the dielectric Q factor is related to loss tangent of the sample material by a participation ratio p_d

$$p \times \tan\delta = \frac{1}{Q_d} = \frac{p}{Q_{crystal}}, \tag{4}$$

where p is the participation ratio of the sample defined as

$$p = \frac{\int_{V_d} \epsilon |E|^2 \, dV_d}{\int_V \epsilon_0 |E|^2 \, dV}, \tag{5}$$

where V_d and V are the volumes of the dielectric sample and the vacuum mode volume in the cavity, respectively.

In order to measure the loss tangent, the quantities $Q_{0,1,2}$ need to be calibrated by characterizing the bare cavity transmission spectrum without the embedded sample. The participation ratio p can be derived from the FDTD simulation results. Therefore, by measuring Q_L, we can estimate the loss tangent of the sample.

The loaded quality factor (Q_L) is derived through power decay measurements. For this purpose, we consider the cavity operating at a fixed resonant frequency, after the RF source is switched off we observe the linear decay of the power, which is dissipated at the cavity's walls (P_0). The total power also takes into account the power leaked through the input/output couplers (P_1, P_2), as well as the power dissipated in the dielectric sample (P_d), $P_{tot} = P_0 + P_1 + P_2 + P_d$, analogously to Eq. (2). We can define the loaded quality factor as $Q_L = \frac{\omega U}{P_{tot}}$, where ω is the resonant frequency of the cavity and U is the stored energy in the whole volume. When the power in the cavity decays, it is left to "ring down" and the stored energy follows the trend:

$$\frac{dU}{dt} = -P_{tot} = -\frac{\omega U}{Q_L}. \tag{6}$$

Therefore the measured stored power follows the exponential decay:

$$U = U_0 \exp -\frac{t}{\tau_L}, \tag{7}$$

with $\tau_L = \frac{Q_L}{\omega}$. U_0 is the stored energy at $t = 0$, the time in which the RF power is switched off [8].

As the environmental condition changes, the variation of the loss tangent will lead to the change of loaded Q factor:

$$p \times \Delta \tan\delta = \Delta\frac{1}{Q_d} = \Delta\frac{1}{Q_L}. \tag{8}$$

To characterize the dielectric permittivity of the crystal, we need to measure the transmission spectrum by sweeping the frequency of the input signal around the resonant frequency of the microwave mode. The simulated transmission spectrum shows a Lorentzian peak representing the microwave mode that is used for crystal characterization (black curve in Fig. 4). As the environmental conditions vary, the sample exhibits a change in both dielectric constant and loss tangent. The former leads to the shift of the cavity resonance frequency, while the latter changes the bandwidth of the Lorentzian peak. By curve fitting we can retrieve the frequency shift as well as the bandwidth change. As such the resonance frequency shift of a microwave mode is dependent on the real dielectric permittivity of the crystal by:

$$\Delta f = \frac{df}{d\epsilon}\Delta\epsilon, \tag{9}$$

where the value of $\frac{df}{d\epsilon}$ is derived from FDTD simulation for the mode of study.

Moreover, the precision of measuring frequency shifts is determined by the linewidth of the Lorentzian peak determined by the Q factor of the microwave mode with the crystal embedded. Therefore, the high quality of microwave cavity is of critical importance for crystal characterization. Further, the sample volume can also exert nontrivial influence on the precision of measurement. It is noted that there is a trade-off between the participation ratio which determines the response and the amount of dielectric loss induced by the crystal which affects the linewidth.

With the method developed above, we can characterize the dielectric constant and loss tangent of the sample as a function of environment temperature and microwave field power. The dependence of loss tangent and dielectric constant upon temperature and photon number can provide information for the sources of loss of the sample, which can be composed of two-level system (TLS) loss, quasi-particle loss, piezoelectric loss, etc. The understanding of such loss mechanisms will lay the foundation for engineering electro-optic devices for high-fidelity and high-efficiency quantum transduction.

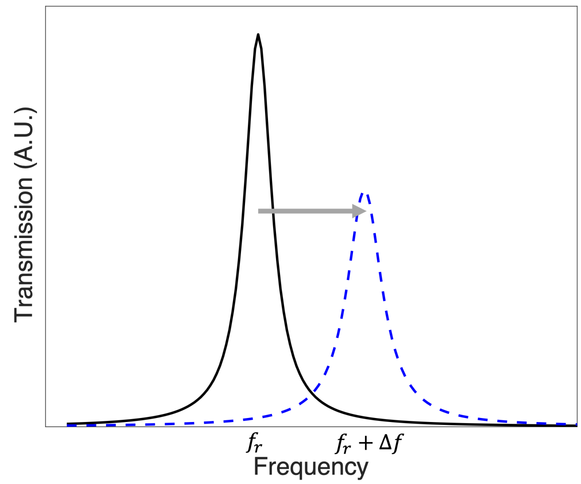


Fig. 4. The expected transmission spectra of the cavity enclosing the crystal which is subject to different environmental conditions. As a result of the change in the dielectric constant and loss tangent of the electro-optic crystal, the central frequency of the transmission spectrum shifts to the blue side and the spectrum gets broadened by additional dielectric loss. f_r is in the order of 7 GHz. Based on simulation, we estimate Δf is around 400 - 600 kHz for $\Delta\epsilon = 0.01$. For this reason, we designed the cavity with high quality factor to achieve higher resolution in the measurement.

V. Conclusions and Outlook

Methods and devices described in this paper pave the way to the first massive microwave characterization of electro-optic crystals at milli-Kelvin temperatures and down to the single photon level. We plan to analyze multiple samples of different noncentrosymmetic materials that could be employed for quantum transduction, i.e. exhibiting a high electro-optic coefficient and low losses at both microwave and telecom frequencies. Although we do not expect to observe relevant TLS-related losses, these can still be present and due to impurities in the sample. We will able to disentangle these mechanisms by scanning the temperature in the cryostat and the amplitude of the microwave field. Additional losses induced by the piezoelectric effect could also be evaluated by measuring microphonics in the microwave resonator. The main scope of this study is to analyze so far unexplored operating regions for these crystals. The findings will guide the design of microwave-optical transducers based on both bulk and thin-film electro-optic materials.

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