Observation of X-rays during heating a pyroelectric crystal by an infrared laser

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Abstract. A pyroelectric X-ray source is proposed, in which a lithium tantalate crystal is heated by an infrared laser with a wavelength of 10.6 μm. X-ray spectra measured during irradiation of the crystal with infrared radiation and during natural cooling of the crystal include characteristic X-ray radiation of atoms contained in the structural parts of the source, as well as bremsstrahlung of electrons with energies above 50 keV. An 8 mm sodium chloride window was used to inject 64 W infrared radiation into a vacuum chamber with the pyroelectric crystal installed.

1. Introduction

The pyroelectric effect has been known for many years and is used for radiation detection, imaging, radiometry and thermometry, energy conversion, etc. [1, 2]. Pyroelectric materials are spontaneously polarized anisotropic dielectrics, the temperature change of which leads to the formation of an electric potential difference along the polarization axis [3]. The potential difference between the surfaces of a pyroelectric sample placed in a vacuum can reach a value of about 100 kV, and it can be used to accelerate electrons [4] and ions [5], as well as to generate X-rays [6, 7] and neutrons [8, 9]. Active research into the use of pyroelectrics to generate ionizing radiation, described in detail by Geuther [3], prompted Amptek, Inc. [10] to develop a compact, battery-powered pyroelectric X-ray source. Such compact radiation sources can be used for X-ray fluorescence analysis (XRF) [11, 12], X-ray absorption spectral analysis (XAS) [13], X-ray imaging [14], treatment [15], and education [16].

For temperature control of pyroelectrics, simple resistive heaters, Peltier devices (TEC), or liquid nitrogen coolers have usually been used. At the same time, the use of laser radiation [17–19] makes it possible to more accurately control the power supplied to the pyroelectric sample during heating and makes it possible to control the duration of irradiation, providing the possibility of both continuous heating and short pulse exposure. To date, prototypes of X-ray sources have been proposed, in which lithium niobate crystals (LiNbO3), placed in a vacuum, were heated with blue (470 nm) [20] or ultraviolet (266 nm) [21] lasers.

Here we present the X-ray spectra measured by heating a lithium tantalate ($LiTaO_3$) crystal with an infrared laser and by natural cooling.

2. Experiment

The scheme of the experiment performed at Belgorod National Research University (Belgorod, Russia) is shown in figure 1. The lithium tantalate crystal [22] with dimensions of 20 × 20 mm^2 and a thickness of 10 mm was placed in a vacuum chamber, which is a standard KF40 stainless steel cross. An Oerlikon Leybold Turbovac 50 high-vacuum pump was connected to one of the four KF40 flanges through a vacuum valve. The valve was used to set the air pressure in the vacuum chamber to 1×10^{-4} mbar. During the experiment, the pyroelectric crystal glued to a holder made of duralumin (2024 aluminum alloy) using Epotec HD21D electrically conductive epoxy resin was irradiated with infrared radiation with a wavelength of 10.6 μm, which is outside the transmission range for lithium tantalate (approximately 0.4–5.5 μm [23]). The source of infrared radiation was the carbon dioxide (CO_2) laser of an industrial cutting machine. An infrared radiation beam with a power of up to 80 W and a transverse diameter of about 1 mm entered the vacuum chamber through an 8 mm thick sodium chloride (NaCl) window, transparent to radiation with a wavelength of 0.2 to 20 μm [24]. A massive brass target with a 10-mm hole was mounted at 10 mm from the crystal surface.

X-ray radiation generated by a change in the temperature of the pyroelectric crystal escapes the vacuum chamber through a Mylar window 100 μm thick, transparent for radiation with an energy of more than 3 keV [25]. A semiconductor detector Amptek XR100T with cadmium telluride (CdTe) crystal 5 × 5 mm^2 in size and 1 mm thick, installed at 115 mm from the axis of the laser beam, registered the X-ray radiation spectra.

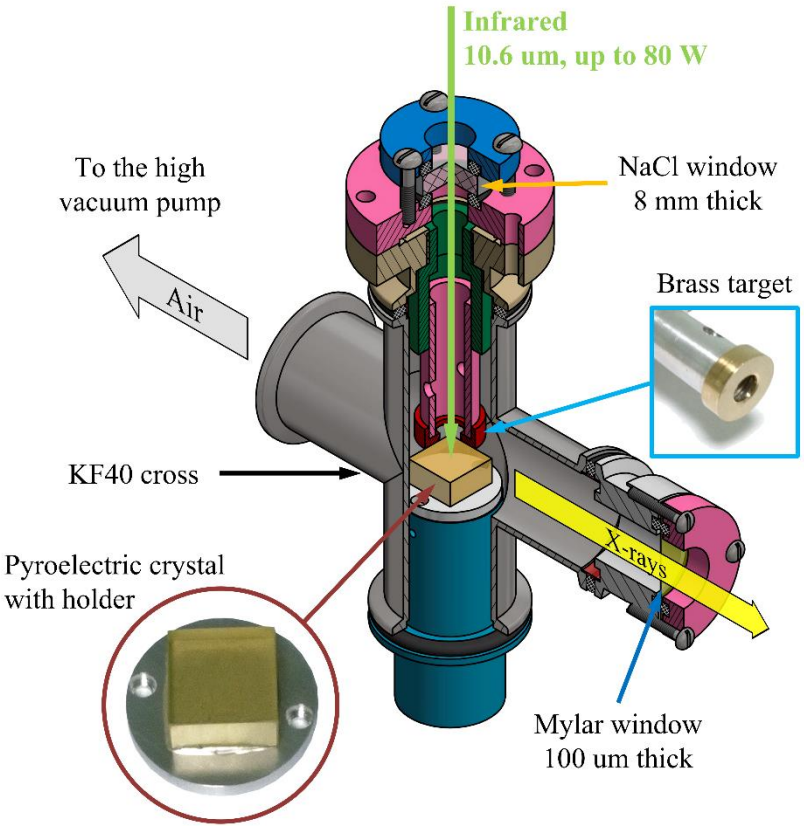

Figure 1. Experimental layout. Infrared radiation enters the evacuated KF40 cross through a sodium chloride window, passes through a hole in the brass target, and hits the lithium tantalate crystal. X-rays produced by changing the temperature of the pyroelectric crystal are output through the Mylar window.

3. Results

During the experiment, infrared radiation with a power of 64 W was generated by the laser, entered through the sodium chloride window into the vacuum chamber, passed through the hole in the brass target, and interacted with the lithium tantalate crystal. Under the action of the beam, the temperature of the crystal increased, and a potential difference was formed between the surfaces of the crystal and the target. This potential difference accelerated the electrons emitted from the pyroelectric surface [17, 26] towards the target, as shown in figure 2(a). When the accelerated electrons hit the target, characteristic X-rays (CXR) [27] and bremsstrahlung are generated. Figure 2(b) shows the X-ray spectrum measured by irradiating the pyroelectric with infrared radiation for 60 seconds. The spectrum contains narrow peaks corresponding to CXR of the copper (Cu) and zinc (Zn) atoms that make up the target, as well as the iron (Fe) atoms contained in the vacuum chamber. The spectrum also contains a wide pedestal with end-point energy of about 53 keV, corresponding to electron bremsstrahlung. The selected radiation power and duration of exposure are dictated by the crystal durability. Exceeding these values (64 W and 60 s, respectively) led to the destruction of the crystal due to stresses caused by rapid inhomogeneous heating.

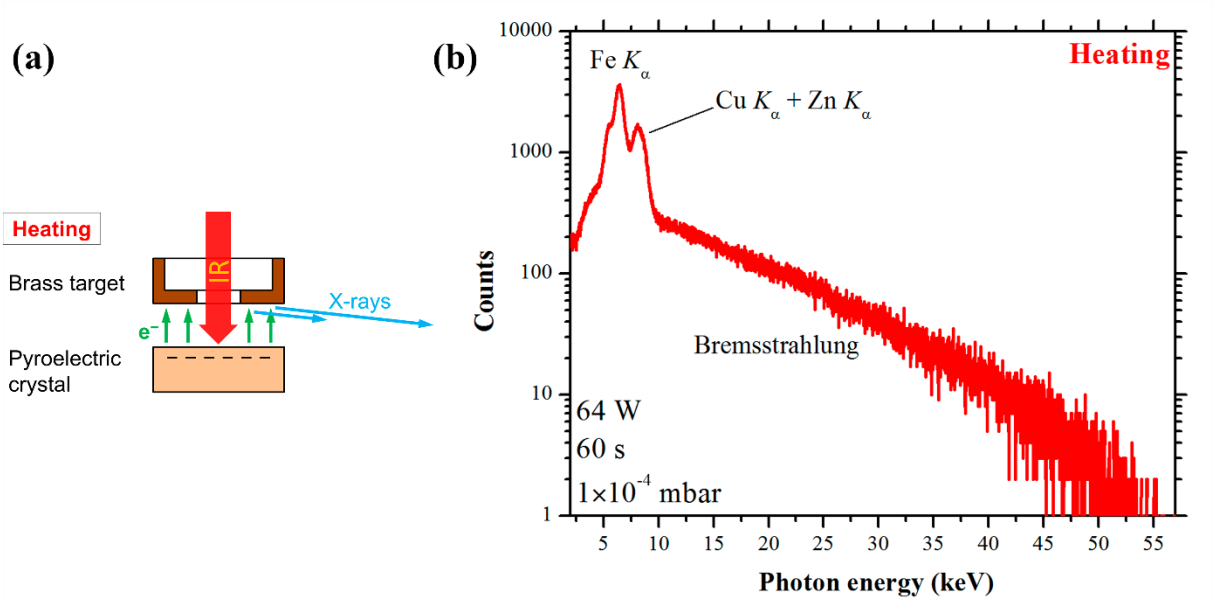

Figure 2. Heating the pyroelectric with the infrared laser (a). When a pyroelectric crystal is heated, an electric field is formed between its surface and a brass target, which accelerates electrons. The X-ray spectrum (b), which is generated during the deceleration of electrons in the target, includes bremsstrahlung and peaks of the characteristic X-ray radiation of target and vacuum chamber atoms.

After turning off the laser, the crystal temperature began to decrease due to natural cooling. Upon cooling, the polarity of the charge formed on the crystal surface changed, and the electrons began to accelerate from the target to the crystal (figure 3(a)). In this case, the X-ray spectrum (figure 3(b)) contains the CXR peaks of tantalum (Ta) atoms contained in the pyroelectric crystal. The low intensity of X-ray radiation and the low value of the end-point energy of bremsstrahlung (about 36 keV) are associated with a low temperature change rate in comparison with the case of heating. A low cooling rate was required to avoid damage to the crystal and increase its lifetime.

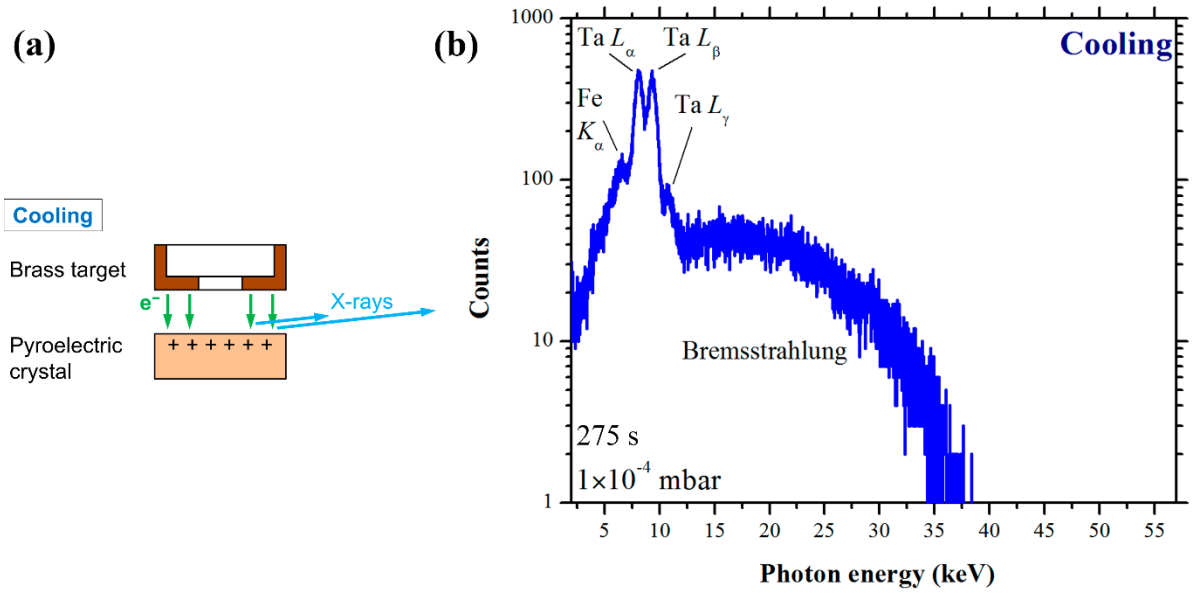

Figure 3. Natural cooling of the pyroelectric (a). When a pyroelectric crystal is cooled, an electric field is formed between its surface and a brass target, which accelerates electrons. The X-ray spectrum (b) generated during the deceleration of electrons in the crystal includes bremsstrahlung and peaks of the characteristic X-ray radiation of crystal and vacuum chamber atoms.

4. Conclusion

We have experimentally demonstrated the possibility of using infrared radiation for heating pyroelectrics in sources of ionizing radiation. The presented radiation source generated X-rays with end-point energy of 53 keV and an intensity of about 6×10^6 photons per second per steradian when a lithium tantalate crystal was heated by a conventional carbon dioxide laser. In addition, lasers provide remote heating, which makes it possible to create a wireless source with an X-ray emitter no larger than a subminiature vacuum tube.

CRediT authorship contribution statement

R M Nazhmudinov: Validation, Formal analysis, Investigation, Writing - Original Draft, Writing - Review & Editing, Visualization; **A S Kubankin:** Conceptualization, Methodology, Resources, Supervision, Project administration; **A N Oleinik:** Resources; **A A Klenin:** Resources.

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