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Fabrication of pyroelectric laser-energy meters and their characterization using Nd:YAG laser of variable pulse-width

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Abstract

This paper reports the fabrication and performance-testing of two types of laser-energy meter based on the pyroelectric effect in a crystal (triglycine sulphate, TGS), namely metal-coated TGS and black-coated TGS. A comparison is made between these two types of sensors in terms of response time and sensitivity. Variation of the output response of the energy meter with laser pulse-width is analysed and verified. When the pulse-width of the laser is greater than the response time of the energy meter, the output signal is found to depend on the input capacitance of the circuit. Experiments done with different laser pulse-widths confirm the mathematical formulation given in this paper. The basic parameters for designing a laser-energy meter are described, and the results are validated against experimental data obtained by measurements with an Nd:YAG laser of variable pulse-width.

Keywords: Pyroelectric; Laser-energy meter; Thermal time constant; Pulse width; Capacitance

1. Introduction

Detection of radiation is of importance in many branches of science and technology. Since electromagnetic radiation encompasses a wide spectrum, the detection devices and techniques depend on the wavelengths and energies involved. Detection of radiation involves measurement of its specific characteristics. These may be classified as: (a) spectrum and spectral width; (b) intensity distribution in terms of Watt/Hz/cm^2 or photons/cm^2/s; (c) spectral or angular distribution; (d) temporal variation of intensity and spectrum; (e) phase information in the case of coherent radiation; (f) noise intensity and distribution [1]. Different types of photodetectors may have widely differing characteristics as far as these features are concerned. Their performance is determined by the basic principle of operation, material properties, geometry, operating temperature, as well as post-detection signal handling.

Lasers are high-intensity coherent sources of photons. To measure the output energy of lasers, different kinds of photodetectors are used. These are commonly called laser-energy meters or power meters. There are three different kinds of them, depending on the type of sensing material used: (i) photodiodes (semiconductor-junction based); (ii) thermal absorbers (thermopile based); (iii) thermal absorbers (pyroelectric-effect based). For photodiodes the signal is proportional to the number of incident photons. They can be used to measure both the power of a continuous laser source, as well as the energy of the repetitive pulses. Thermopiles respond to the power of incident radiation. Pyroelectrics produce a signal related to the amount of incident radiation energy. Pyroelectric detectors are used to measure the energy of the repetitive pulses of a laser [2].

Different models of pyroelectric energy meters are available commercially. There are three ways in which a pyroelectric detector may be used: (a) to detect a signal modulated at a constant frequency; (b) by combining a detector operating in this mode with a frequency-equalizing amplifier, a detector with a very short (less than 1 μs) response time may be

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produced (such a configuration is suitable for observing transient signals such as laser pulses); (c) the pyroelectric element may be used to store and measure the total charge liberated by a transient signal [3]. The working principle of a laser-energy meter is based on the third of these modes of operation.

2. Voltage generation in pyroelectric crystals

Out of the 32 crystal classes, only 10 are polar. Only these classes can exhibit the pyroelectric effect [4]. Pyroelectric crystals are spontaneously polarized. In such crystals one observes a change ΔP_i^{s} in the spontaneous polarization when the temperature is changed by ΔT (this is the pyroelectric effect, described by the equation $\Delta P_i^{\mathrm{s}} = p_i \Delta T$, where p_i is a component of the pyroelectric tensor of the crystal). Ferroelectric crystals are a subset of pyroelectric crystals: they have the additional property that the spontaneous part of their polarization can be reversed by a sufficiently strong applied electric field [4,5].

At equilibrium the depolarization field due to the polarization discontinuities at the surface of a pyroelectric crystal is neutralized by free charges. When the crystal temperature is changed, the spontaneous polarization changes, so that an excess of free charge appears on the polar faces of the crystal. This gives rise to a flow of current in the crystal and external circuit [6,7].

Fig. 1 shows the equivalent circuit for a pyroelectric energy meter. For most of the pyroelectric measurements, the crystal is supported in a manner which allows it to expand freely, so that for a slow and uniform change of temperature, there is no constraining stress: $\Delta X_i = 0$. Then the total change in the electric displacement vector due to changes in temperature and applied electric field E is

$$\Delta D_i = \varepsilon_{ij}^{X,T} \Delta E_j + p_i^{E,X} \Delta T, \tag{1}$$

where $\varepsilon_{ij}^{X,T}$ are permittivity-tensor components at constant stress and temperature.

The current density in the crystal is given by

$$J = \sigma E + \frac{\mathrm{d}D}{\mathrm{d}t}, \tag{2}$$

where σ is the conductivity of the crystal along the polar axis.

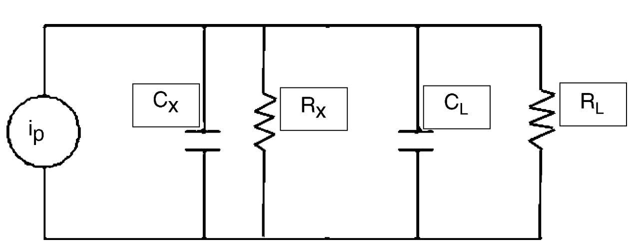

Fig. 1. Schematic circuit diagram of pyroelectric energy meter.

If the polar faces of the crystal are connected to an external circuit, then, for continuity:

$$AJ + \delta C_{\mathrm{L}} \frac{\mathrm{d}E}{\mathrm{d}t} + \frac{\delta E}{R_{\mathrm{L}}} = 0, \tag{3}$$

where C_{L} and R_{L} are the load capacitance and resistance, respectively and A and δ are the electrode area and electrode separation, respectively. Combining Eqs. (1)–(3), we get

$$A\left(\sigma E + \varepsilon \frac{\mathrm{d}E}{\mathrm{d}t} + p\frac{\mathrm{d}T}{\mathrm{d}t}\right) + \delta C_{\mathrm{L}} \frac{\mathrm{d}E}{\mathrm{d}t} + \delta \frac{E}{R_{\mathrm{L}}} = 0,$$

or

$$(C_{\mathrm{X}} + C_{\mathrm{L}})\frac{\mathrm{d}V}{\mathrm{d}t} + \left(\frac{1}{R_{\mathrm{X}}} + \frac{1}{R_{\mathrm{L}}}\right) V = -Ap\frac{\mathrm{d}T}{\mathrm{d}t} \tag{4}$$

Here external voltage $V = E\delta$, crystal capacitance $C_{\mathrm{X}} = \varepsilon A/\delta$, and resistance $R_{\mathrm{X}} = \delta/\sigma A$. This equation can be rewritten as follows:

$$C\frac{\mathrm{d}V}{\mathrm{d}t} + \frac{V}{R} = -Ap\left(\frac{\mathrm{d}T}{\mathrm{d}t}\right), \tag{5}$$

where R and C are the parallel crystal-load parameters ($C = C_{\mathrm{X}} + C_{\mathrm{L}}$ and $R = (1/R_{\mathrm{L}} + 1/R_{\mathrm{X}})^{-1}$).

Multiplying and dividing by $c'\delta$, where c' the volume specific heat, and introducing a function $F(t)$ defined below, Eq. (5) can be further recast as follows:

$$\frac{\mathrm{d}V}{\mathrm{d}t} + \frac{V}{CR} = -\left(\frac{Ap}{c'\delta}\right)\left(\frac{1}{C}\right)F(t), \tag{6}$$

with

$$F(t) = c'\delta\left(\frac{\mathrm{d}T}{\mathrm{d}t}\right).$$

We interpret T as the space-averaged rise in the temperature of the crystal when the laser pulse is incident on it:

$$T = \frac{[\int_0^{\delta} \theta(x)\mathrm{d}x]}{\delta},$$

where $\theta(x)$ is the rise in temperature at a distance x inside the ferroelectric slab of thickness δ. Similarly, $F(t)$ is the space-averaged energy flux per unit area absorbed by the detector. We assume that, at frequencies much lower than the lowest resonant frequency, the term due to thermal stresses is zero. The change in capacitance with respect to time is neglected because, at room temperature, the change in dielectric constant with temperature is small [8].

For the boundary condition $V_0 = 0$ at $t = 0$, the solution of Eq. (6) can be written as

$$V_0 = \left(\frac{Ap}{c'd}\right)\left(\frac{1}{C}\right)\exp\left(\frac{-t}{\tau_{\mathrm{e}}}\right)\int_0^t \exp\left(\frac{\tau}{\tau_{\mathrm{e}}}\right) F(\tau)\,\mathrm{d}\tau, \tag{7}$$

where $\tau_{\mathrm{e}} = RC$, the electrical time constant of the circuit.

The working principle of a pyroelectric energy meter is a special case of Eq. (7). Consider a pulse of radiation absorbed near the surface of a relatively thick plate of the pyroelectric