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Implementation of a programmable electromechanical chopper with adjustable frequency and duty cycle for specific heat measurements

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ABSTRACT

A hard disk mechanism was used as an electromechanical light chopper controlled by software developed in LabVIEW with an accuracy of ±0.01 Hz in frequency to realize specific heat measurements. This chopper can be used in applications in experimental techniques in which low-frequency light excitation is required. The software provides an user interface to set the excitation frequency and its duty cycle. The evaluation of the efficiency was measured by installing the device in a fully automated high-resolution AC calorimetry system. The device provides a light cutter signal with a frequency varying from 1 mHz to 40 Hz. Employing the desired wave function, the excitation mode provided by this design can be used under theoretical models proposed for the specific heat technique, obtaining an increased efficiency in the measurements of the specific heat response for the studied materials. This paper reports the performance characteristics of the technology of an asymmetric CA-chopper, which can optimize efficiency in capturing the measurement of the response of specific heat of any given study material in a high-resolution ac calorimetry system. The chopper consists entirely of the positioning mechanism of a hard disk.

1. Introduction

Optic choppers are devices used to vary and cut off the light rays at either irregular or fixed time intervals. The technologies used for the design of optical choppers include liquid crystal optical shutters, rotating blinds, moving pallets or forks, among others. By deploying variations in the frequency of the chopper optical blade, the light frequency can vary.

Conventional optical choppers contain a metallic circular disk that has holes at either regular or irregular intervals that are attached to a rotary motor, which rotates at either constant or variable speed. The variable frequency rotation of the disk looks like small fans. They have a slotted disk mounted on the head of an engine. It can be used in a variety of frequencies by adjusting the motor speed. Either the optical blade interrupts the light beam or therefore, passes through the holes can calculate the frequency of light calculated using the frequency of the blade. An optical switch detects the position of the disk and provides a reference output to automatically adjust the switching frequency. The optical blade finds its main advantage in achieving a regular frequency beam.

The optical chopper can be operated either by mechanical or electronic means [1,2]. The chopper of the rotation optical disk is used in situations where the frequency and size of the opening (duty cycle) are constant, which is widely used in laboratories and research institutions where the switching frequency is set by the operator [3,4]. The size and number of openings determine the period and the excitation frequency [5]. Optical choppers are widely used in electronic products such as lamps, cameras, film projectors, signal detection and recovery, lasers and other signaling devices [6–8]. Depending on the needs and the degree of accuracy required, the optical chopper finds widespread use in industry, scientific research, aerospace, medical and military applications [9,10]. Optical shutters on the contrary, are mechanical or electronic devices used to control the amount of time that a light sensitive material is exposed to radiation.

The optical shutters differ from the disk chopper, in that for optical shutters a simple periodic on-off cycle is not limited. They follow an arbitrary pattern, varying from openings and closings. The optical shutters are useful for cutting low frequency, particularly when it has a slow behavior. Optical choppers and optical shutters come in various configurations: variable frequency rotating disks, fixed frequency pallet cutters, optical shutters, high frequency devices for applications where the functions light flux

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modulation are necessary, and where communications with optical fiber is required [1,11,12].

Resonant choppers are suitable to cut light when one wishes a known fixed frequency, a small size and long service life. The fork choppers resemble musical tuning forks with small oscillatory paddles. They vibrate in response to an AC-signal at a specific resonance frequency. Optical fork choppers are extremely durable and have no wear parts, basically they have no moving parts to wear avoiding errors of precision in optical experiments [13,14]. As a result, they are often used in applications of high acceleration and vibration. They can be used for extreme temperature or in vacuum or microscopic applications [7,8,15]. Due to the compact size and being made of special alloys, they can be used in high temperature applications [1]. Also available in the market is the piezoelectric chopper for microscopic applications [7,8,14,16], RX cutter [8] and chopper for radiological applications [2]. Gravitational wave observatories such as the Laser Interferometer Gravitational-Wave Observatory (LIGO) uses an optical blade pitch in a Michelson interferometer for detecting gravitational waves [17].

Among the different techniques for measuring the specific heat, in the experimental setup an optical excitation is required, which can be either continuous or modulated. The modulated excitation is provided using mechanical light cutters, requiring high precision and accuracy of the light excitation function. In this case, the use of an electromechanical light cutter (known as chopper), programmable in its duty cycle, presents an instrumental advantage to optimize the signal measurement of specific heat, to be able to adapt the frequency of excitation to the conditions of the material studied. The signal optimization consists of obtaining the maximum possible amplitude representing the thermal response of the sample to an external thermal periodic stimulus of heating, at a frequency and duty cycle suitable for that particular sample. A light source rich can provide this external stimulus in infrared frequency.

In this work, a positioning mechanism of a hard disk such as an electromechanical chopper suitable for multiple applications in experimental techniques such as photoacoustic, photoreflectance, in which low-frequency chopper excitation was used. Particularly, the device has been used for measurements of specific heat using the high-resolution AC calorimetry technique. High resolution AC calorimetry is probably the most sensitive technique for detecting the response of specific heat of a sample as a function of temperature [18–22]. In the traditional technique for measuring the specific heat under adiabatic conditions, a known amount P_0 of heat is supplied to the sample. This power is supplied by periodic light falling over the sample, which is thermally isolated and so ΔT_{AC} represents temperature change measured over the sample.

Normally no thermal stabilization times at each measurement point are known, and it is assumed that the times on average of τ_s and τ_{int} are equal, with the disadvantage that the times of excitation-relaxation provided by the chopper do not necessarily correspond to the times, τ_s required for the sample to absorb the sufficient thermal energy that it naturally can absorb, and the time τ_{int} required for the sample to reach thermal equilibrium with the heat reservoir.

The instantaneous light output supplied to the sample-bath by the chopper is absorbed or dissipated, depending on the physical properties of the sample and the thermodynamic conditions of the system. The periodic supply of power (light) must be synchronized to these conditions, adapting the form and frequency of the light excitation power to the excitation and relaxation times of each sample and the system, thus optimizing the measurement process. Due to the delay time of the opening and closing of the blade cutter being much less than the heating and cooling time (1 s), of the study sample, it is not considered for actual application. To date, except for Ref. [23], no studies have been reported showing any relationship between the amplitude of the specific heat response and the half-cycle of excitation provided by the chopper.

The general expression reported in the literature [19,20] for the specific heat c_P is:

$$c_P = \frac{P_0}{\Delta T_{\mathrm{AC}}\,\omega\,\rho_s\,d}\left(1 + \frac{1}{\omega^2\,\tau_s^2} + \omega^2\tau_{\mathrm{int}}^2 + \frac{2\kappa_b}{3\kappa_s}\right) \tag{1}$$

where ΔT_{AC} represents the temperature oscillations of the sample produced by the light chopper, τ_s is the relaxation time of the sample with the thermal bath, τ_{int} is the internal relaxation time of the sample, κ_s and κ_b are the thermal conductivities of the sample and bath, respectively. Expression (1) can be summarized as Eq. (2), if the light power P_0, the light-frequency ω, the density of the sample ρ_s, the thickness of the sample d are considered constant, and if it is considered that the term in brackets has a value approximately equal to 1,

$$c_P = \frac{P_0}{\Delta T_{\mathrm{AC}}} \tag{2}$$

That is, by measuring the temperature oscillations of the sample ΔT_{AC} for which a thermocouple that is in contact with the sample is used, the specific heat of the c_P sample is obtained. By measuring the sample-reservoir average temperature (T_{DC}), using a thermocouple that is attached to the reservoir and measuring the average temperature of the sample, graphs of c_P as a function of temperature (T_{DC}) are obtained. By using the electromechanical chopper that is reported in this work whose form and frequency of excitation power can be adapted to the excitation and relaxation times τ_s and τ_{int} of each sample and the system, it is possible to optimize the measurement of the response of the specific heat of a metal indium sample, in a high-resolution AC calorimetry system.

2. Implementation and results

Fig. 1 illustrates a block diagram of the AC calorimetry technique. The study sample is excited with a source of light cut periodically by the chopper. The infrared component of the excitation source generates phonon activity in the sample. The vibration of the lattice induces the atoms or molecules to a characteristic oscillatory movement of each material, reason for which there will be an optimum frequency of excitation for which the thermal response of the material will be maximum. According to Eq. (1), the specific heat value depends on the half-periods (excitation and relaxation), which have been experimentally determined to be different depending of the nature of the sample, which implies that the excitation function must have the appropriate shape to the specific conditions of each material, thus improving the resolution of the technique. In the experimental set up, this difference is not taken into account for the light power supply [23]. The increase of the specific heat response by varying the half-period of the periodic light excitation signal on the sample during the specific heat measurement has been previously reported [23].

The light electromechanical cutter is totally controlled by a software developed in LabVIEW. The system consists of a signal conditioning stage which adjusts the voltages delivered to the electromechanical chopper by means of the parallel port of the computer which is the one that sends the control signal with its respective frequency and useful cycle. The light cutting blade is $3.5 \times 2.0\ \mathrm{cm}^2$ in area and is attached to the moving axis of the system, see Fig. 2. The operating principle is based on the interaction of the magnetic field generated by the axle-mounted coils and the magnets mounted on the structure, producing the oscillating movement of the blade which is on the axis and the end as shown in Fig. 2. The chopper blade sweeps a wide enough angle to allow