ELECTRICAL CHOPPED FREQUENCY CIRCUIT FOR CHARACTERIZING PYROELECTRIC SENSOR

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Abstract: *In this work an electrical chopped frequency circuit was fabricated to convert direct current voltages to equivalent pulsating voltages in the range of infrared spectra to characterize and evaluate pyroelectric sensor. The proposed circuit is composed of computer-controlled Arduino UNO circuit board to generate the chopped required electrical pulse, transmitting circuit convert this electrical pulse to infrared signal, pyroelectric sensor with amplification circuit, and an oscilloscope or a voltmeter as a signal detector. This circuit was tested and evaluated at room temperature for polyvinyldene difluoride (PVDF) sensor with changing the frequency range from 0.01 Hz to 100 Hz. The voltage responsivity, noise equivalent power (NEP) and detectivity of PVDF was tested and measured in the range from 0.01 Hz to 100 Hz. The voltage responsivity of PVDF pyroelectric sensor was found to be 117 V/W at 0.5 Hz, NEP was about* 4.42×10^{-7} *W/Hz*$^{1/2}$ *at 100 Hz and the detectivity was equal to* 1.12×10^{6} *cmHz*$^{1/2}$*/W at 100 Hz*

Keywords: *Electrical Chopped Frequency, Pyroelectric Sensor, Voltage Responsivity, Noise Equivalent Power, Detectivity.*

1. Introduction

Pyroelectric sensors have found a wide range of applications in thermo-vision, remote temperature measurement, monitoring and measurements of laser emission parameters, military and civil security systems [1]. For these applications a high responsivity and high detectivity are required. In order to get maximum responsivity, several approaches have been already investigated, such as the appropriate choice of pyroelectric material, special construction techniques to reduce heat loss from the sensitive element [2].

Pyroelectric sensors have many properties in common with other thermal converters. In particular, they show uniform spectral characteristic in a relatively wide range of radiation wavelength. Unlike other thermal sensors, the output signal of the pyroelectric sensor depends on thermal change in pyroelectric element, and not on the temperature value. The response of a pyroelectric sensor is limited mainly by the electric parameters of the equivalent circuit and the proposed amplification circuit [3].

The performance of pyroelectric sensors has been enhanced through the improvement of pyroelectric materials, fabrication techniques, sensor layout, and sensor systems [4]. In general, the incident infrared is periodically chopped for the ordinary pyroelectric sensor in order to generate a continuous output voltage or current. However the chopping system is large in size, requires high power, and shows low reliability.

Bischoff et al had published a patent that described an electronic circuits used for converting direct current voltages to equivalent pulsating voltages using a bridge circuit having a diode in each of its four arms which alternately conducts and blocks the direct current voltage by use of an activating alternating voltage [5].

This work is aimed to build a new chopper frequency by using a simple electrical circuit. The proposed modulation pyroelectric sensor is composed of a chopping system that includes an Arduino UNO board programmed through the PC to generate multiple wavelengths, transmitting circuit to convert the wavelengths generated to infrared (IR) signal with the range of chopped frequency. The voltage responsivity, noise equivalent power and detectivity of PVDF sensor are measured. The originality of this work is provided a new and simple technique for pyroelectric properties measurement.

2. Principle of Pyroelectric Sensor

The pyroelectric device is a thermal sensor, wherein the light power is converted to an electrical output. Its response is independent of the wavelength of light or radiant energy it receives. The pyroelectric sensor is especially useful for the near to far IR because of its high sensitivity and responsivity [4].

Pyroelectric sensor is a capacitor formed by depositing metal electrodes on both surfaces of the thin slice of pyroelectric material. Absorption of the radiation pulse of power P(t) by the pyroelectric material results in a change in its temperature with the value of dT, which causes a polarization change. This results in displacement of the electric charges in the pyroelectric material, hence a displacement current $I_P(t)$ occurs.

Figure 1, shows the equivalent circuit of the pyroelectric sensor and the amplification circuit. The pyroelectric sensor is connected to a resistor R_E, which represents either the internal leakage resistance or a combined input resistance of the interface circuit which is connected to the sensor. The equivalent electrical circuit of the sensor consists of three components: the current source generating a heat induced current Ip(t), the sensor's capacitance, C_E, and the leakage resistance R_E. In the diagram the equivalent parameters of the load preamplifier circuit: the capacitance C_d, and resistance R_d are placed.

Assuming the uniform structure of the pyroelectric material and uniform heating, the current $I_P(t)$ may be determined from equation [6]:

$$I_P = p.\frac{dT}{dt}.S \qquad (1)$$

where:

p: pyroelectric coefficient.

dT/dt: rate of temperature changes of the pyroelectric material.

S: surface area of the sensor electrode.

Let us assume that there are no additional heat losses, the duration of incident radiation pulse t_I is very short and it meets inequality [7]:

$$t_I \ll \tau_E \ll \tau_{TH} \qquad (2)$$

where:

τ_E: electrical time constant of the whole electrical circuit:

$$\tau_E = \frac{R_d \cdot R_E}{R_d + R_E} \cdot \left(C_d + C_E\right) \qquad (3)$$

τ_{TH}: Thermal time constant of the pyroelectric sensor and is the time for which incident radiation power on its input surface responds with electrical signal at its output.

In practice, the electrical time constant τ_E, determined from (3), depends on the chosen value of the sensor's capacitance C_d and input resistance R_E of the voltage preamplifier. Choosing an appropriating large value of R_E or limiting the maximal duration of the radiation pulse incident, one can assume that inequality in (2) is satisfied as far as the relation between the pulse duration and the electric time constant of the circuit and the thermal time constant of the sensor are considered. This means that the value of output voltage signal U(t) depends on the integrating of current source I_p, obtained in the loading of the equivalent capacitor $C = C_d + C_E$. The value of the output voltage signal from the pyroelectric sensor is given by:

$$U = \frac{1}{C}\int_{t_I} I_p(t)\, dt \qquad (4)$$

The output signal from the pyroelectric sensor can be in the form either current or voltage, depending on the application. The pre-amplification stage of the readout electronics is the most crucial part. Special designs need to be selected for lowering the electronics noise contribution to below, the dielectric noise of the pyroelectric element. The classical solution with discrete electronics is the use of a *JFET* in a source follower circuit Figure 1. *JFET*s exhibit smaller noise levels than MOSFETs at low frequencies required. For voltage amplification, the effective parallel resistor in Figure 1 needs to be smaller than the input resistor of the *JFET*, which amounts typically to 10^{11} Ω [8-9].

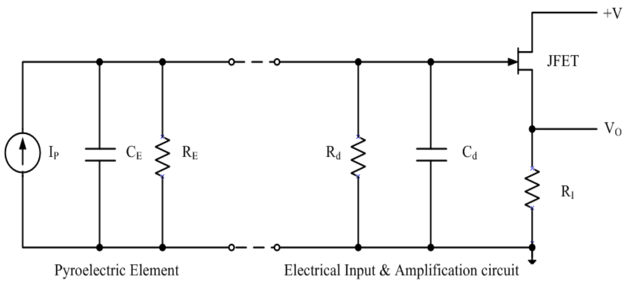


Fig. 1. Electrical equivalent circuit of the pyroelectric sensor and the amplification circuit

3. Measurement Methods of Pyroelectric Properties

The measurement techniques of pyroelectric properties mainly voltage responsivity, noise equivalent power and detectivity are classified into two types such as static and dynamic techniques. In the static technique, a pyroelectric sensor is heated directly and the change of spontaneous polarization can be detected with pyroelectric currents or voltages. This technique cannot investigate the frequency dependence of pyroelectric property and the polarization state is destroyed. On the other hand, dynamic technique senses the variation of spontaneous polarization due to the small temperature change with the pyroelectric current or voltage. Dynamic technique can investigate the frequency dependence of pyroelectric property with no destroy of polarization state [10]. The scheme diagram of the measurement pyroelectric properties is showed in Figure 2. A light beam emitted from a halogen lamp is focused, after being mechanically chopped, on the pyroelectric sensor that is fixed in the sensor chamber. The voltage from the temperature sensor can be measured by a lock-in amplifier. Mechanical choppers consist of a slotted disk that is interfaced to a motor and a driver circuit. The stability of the motor driver dictates the beam characteristics (peak velocity, velocity spread, and intensity) and also limits the day-to-day reproducibility of these parameters. Therefore, to minimize any fluctuations on the velocity and chemical composition of pulsed beams, the driver circuit has to be extremely stable [11]. The system shown in Figure 2 discuss how to generate mechanical chopper frequency to characterize the pyroelectric sensor and it focused by the mirror and lens to incident on the sensor element this system is very complicated and expensive [12-13].

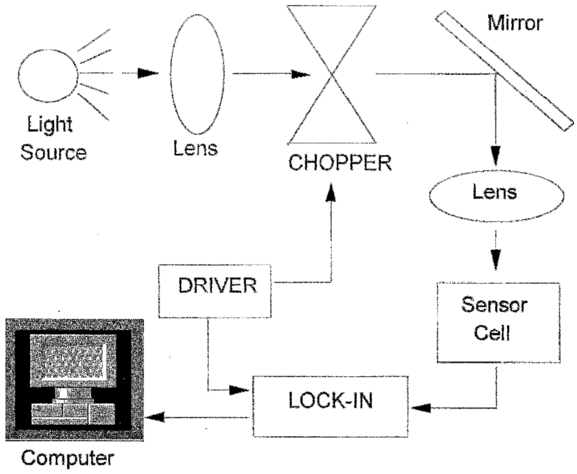


Fig 2. Schematic diagram of a measurement system based on a mechanical chopper

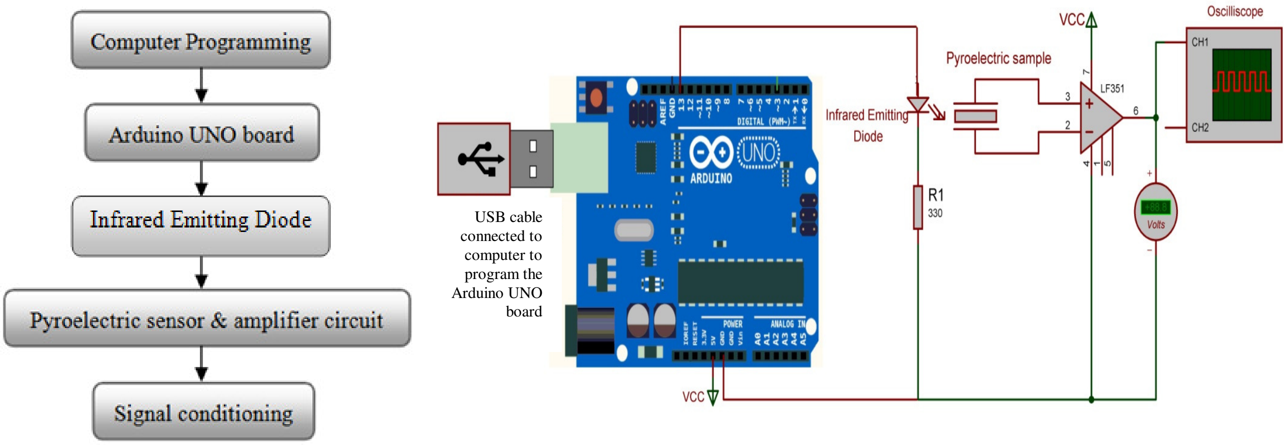
4. Experimental Work

Figure 3 shows the schematic diagram of the pyroelectric sensor measurement circuit. The first part consists of an Arduino UNO board that can be programmed with C language to generate a square wave with modulation frequency in the range of the chopper frequency. Arduino UNO is a micro controller board base that has 14 digital input/output pins 16 MHz ceramic resonator, and a USB. Arduino Uno can be simply connected to a computer with a USB cable or to an AC-to-DC adapter or to a battery to get started [14]. The importance of the Arduino UNO board is very simple to program, very cheap. It has an output voltage +5.0V and ground terminal to the external circuit which helps to build a pyroelectric sensor measurement circuit shielded to Arduino UNO board as shown in Figure 4 without need to the external power supply to activate the circuit components to characterize the pyroelectric sensor. The generated frequency is converted to IR signal by using IR LED transmitter circuit which consists of an IR LED of a radiation source of 35 mW maximum power and is connected to pin number 13 in the Arduino UNO board. It has an output pulsed signal with various frequency ranges. The other terminal of the IR led source is connected to the 330 Ω resistors to ground.

The second part includes both sensing element and the amplification circuit with signal detector. The pyroelectric polyvinyldene fluoride sensor is mounted inside the window of two point probe holder fabricated on a printed circuit board to decrease the noise effect [15]. The holder has two pin output terminals connected to the two terminals input of the amplification circuit as shown in Figure 3b and Figure 4. The amplification circuit is a *JFET* input operational amplifier with an internally compensated input offset voltage. The *JFET* input device provides wide bandwidth, low input bias currents and offset currents to detect variation of change in voltage or current of pyroelectric sensor. After the signal output from the pyroelectric sensor is amplified, it is measured by using an oscilloscope (HITACHI digital storage VC-2060).

5. Testing of the Electrical Measurement Circuit

The circuit is tested and evaluated at room temperature with changing the frequency range from 0.01 Hz to 100 Hz for PVDF as a pyroelectric material. Figure 5 displays the output response of the pyroelectric sensor of PVDF with different incident frequencies of 1, 10, and 100 Hz generated by the Arduino UNO board with pulse width 1000, 100, and 10 msec, respectively. The oscilloscope is used to record and detect the output signal of the pyroelectric sensor with changing the pulse width.



(a) (b)

Fig. 3. Flow chart of block diagram (a) schematic circuit and (b) the pyroelectric sensor measurement circuit

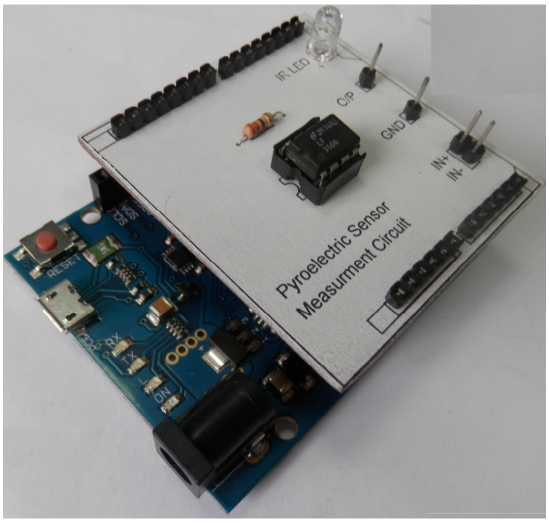


Fig. 4. A prototype of pyroelectric sensor measurement circuit shielded Arduino UNO board

Figure 5a displays the output signal with 5 divisions on the adjusted oscilloscope screen with a 0.2 sec time division. The pulse width was equal to 1 sec when 1 Hz signal was applied. This .gives an excellent agreement between the measured and expected values this ensures the high performance of the proposed designed circuit.

In Figure 5b the output signal appears on the oscilloscope screen to have 10 divisions with 10 msec time division. Then the pulse width is 100 msec which equivalent to 10 Hz. When the time division is adjusted on 10 msec and the oscilloscope screen has 1 division for one pulse then the pulse width is equal to 10 msec which equivalent to 100 Hz as shown in Figure 5c. All detected output signals are compatible with the programmed and transmitted signal frequencies..

6. Characterization of Pyroelectric Sensor

A. Voltage Responsivity

The responsivity of pyroelectric sensors depends on two factors: thermal responsivity of the sensor due to incident radiation and responsivity of pyroelectric material due to temperature changes. Thermal response depends on the temperature changes result from the absorbed radiation [16]. Voltage responsivity "R_V" is defined as a ratio of the pyroelectric voltage output generated ΔV and radiation power incident onto the sensor surface (W_i) [17]:

$$R_V = \frac{\Delta V}{W_i} \qquad (5)$$

where ΔV is function of the frequency. Figure 6 shows the voltage responsivity dependence of modulation frequency for the PVDF thin films sensor. At low modulation frequencies the voltage responsivity is increased to $1/\tau_E$ while at high

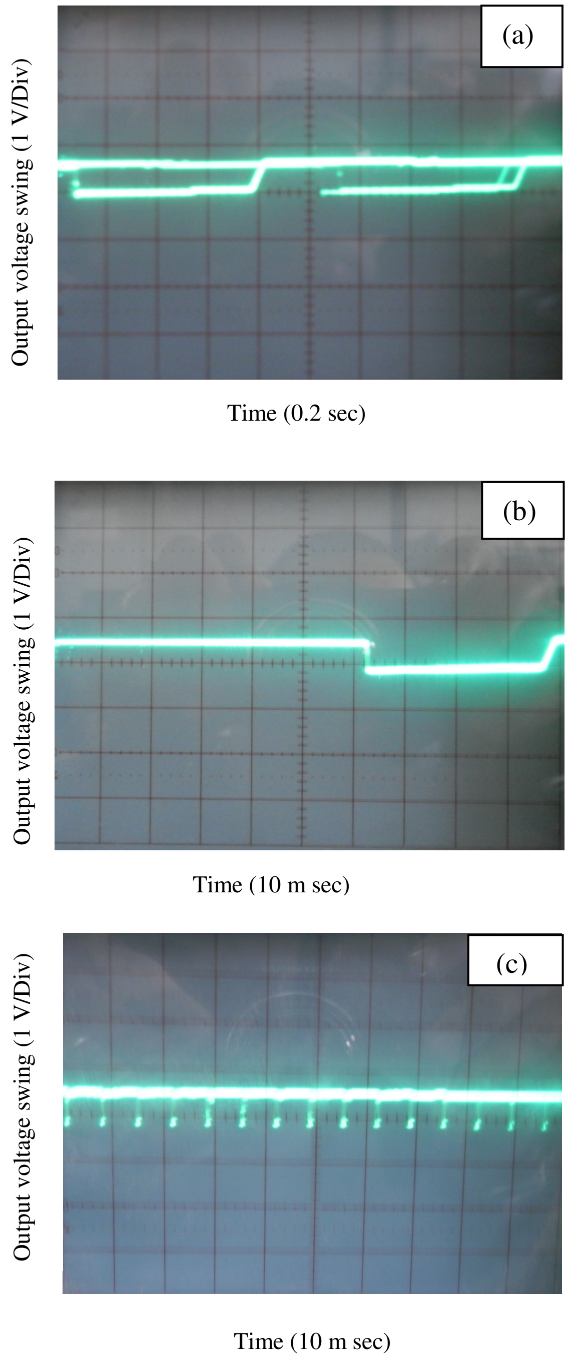


Fig. 5. Output signal detected from PVDF pyroelectric sensor on the oscilloscope at 1 Hz (a), 10 Hz (b), and 100 Hz (c)

modulation frequencies the voltage responsivity is decreased again after $1/\tau_T$.

This behavior can be explained with a theoretical equation for the voltage responsivity of pyroelectric sensor as follows [18]:

$$R_V = \frac{\eta \, p \, A_0 \, R_E \, R_T \, \omega}{\left(1+\omega^2 \tau_E^2\right)^{1/2} \times \left(1+\omega^2 \tau_T^2\right)^{1/2}} \qquad (6)$$

where η is the emissivity, p is the pyroelectric coefficient, A_0 is the sensor area, R_E and R_T are the electrical and thermal resistance, respectively, ϖ is the modulation frequency, τ_E is the electrical time constant, and τ_T is the thermal time constant which are estimated from measurement of the rising and falling edges from the observed output waveforms [19]. As shown in Figure 6, the voltage responsivity increases with increasing frequency for $\omega < 1/\tau_T$ and decrease with increasing frequency for $\omega > 1/\tau_T$. The voltage responsivity of PVDF pyroelectric sensor is found to be 117 V/W at 0.5 Hz. This value of responsivity is agreement with the results obtained by Bauer et al where they found that the voltage responsivity of the integrated PVDF with silicon chip was equalled to 150 V/W [12]. Pyroelectricity is based on the change of the internal dipole moment as a result of temperature change. There are two contributions to the pyroelectric effect:. The 'primary' effect is caused by an internal dipole moment change resulting from rotation of the dipoles or modification of the inter-atomic bonding without a macroscopic deformation of the material. This primary effect should be clearly distinguished from the 'secondary' pyroelectricity that is a result of the deformation which accompanies a charge in temperature. These dipole moments can follow up and be oriented at low modulation frequencies and consequently the response increases. On the other hand, at high frequencies the voltage responsivity decreases again because of displacement of the dipole moments cannot follow the change in the field [20].

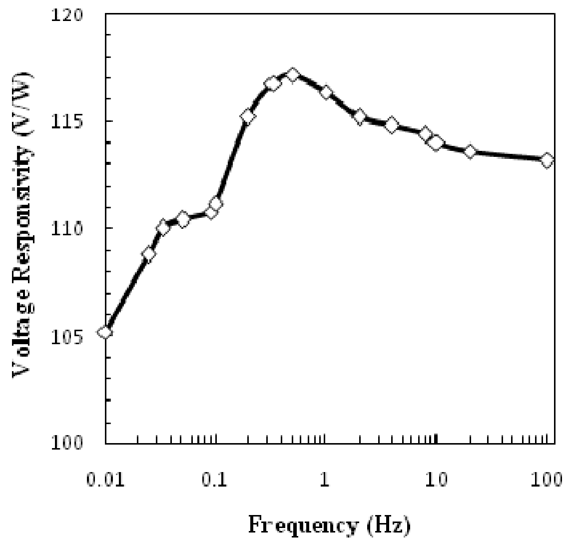


Fig. 6. Voltage responsivity dependence of modulation frequency for the PVDF thin films sensor

B. Noise Equivalent Power

The sensitivity of a sensor is determined by the level of noise in the amplifier output signal. Therefore, the signal-to-noise ratio should be large. The noise level can be described by the so-called noise equivalent power "NEP". It is given as a ratio of total noise voltage ΔV_N and the voltage responsivity R_V [17]:

$$NEP = \frac{\Delta V_N}{R_v} \tag{7}$$

where the total noise voltage is equal to the summation of Johnson noise V_J, thermal noise V_{TH}, and amplifier noise V_A. The frequency dependence of the noise equivalent power of the PVDF sensor is shown in Figure 7. A lower NEP indicates a better pyroelectric sensor. For the PVDF sensor, NEP is about 4.42×10^{-7} W/Hz$^{1/2}$ at 100 Hz.

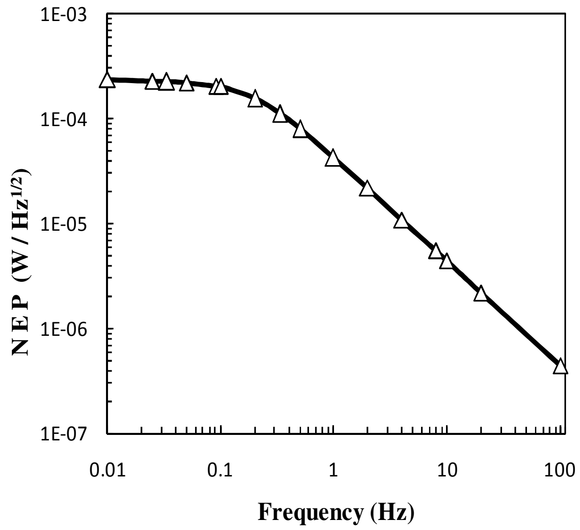


Fig. 7. Noise equivalent power dependence of modulation frequency for the PVDF thin films sensor

C. Detectivity

Detectivity "D*" of the pyroelectric sensor is a parameter with great importance. The detectivity is denoted as D*(*T, F, 1*), where T is the temperature, f is the frequency and 1 stands for bandwidth of 1 Hz. The unit of detectivity is cmHz$^{1/2}$W^{-1}. The maximum possible value of D* to be achieved for a pyroelectric sensor operates at room temperature is 1.98×10^7 cmHz$^{1/2}$W^{-1} [2].At a given frequency, D* is given as a ratio between the square root of sensor area A_0 and the noise equivalent power, which is in (8). Thus, D* can be calculated as [17]:

$$D^* = \frac{\sqrt{A_0}}{NEP} \tag{8}$$

Figure 8 presents the detectivity of PVDF sensor versus modulated frequency. It is observed that the detectivity of PVDF is linearly increased with the frequency after 0.1 Hz. The detectivity of PVDF sensor is equal to about 1.12×10^6 cmHz$^{1/2}$/W at 100 Hz.

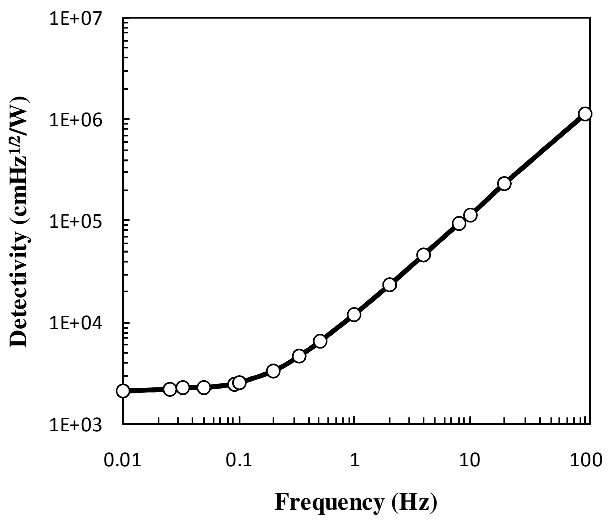


Fig. 8. Detectivity dependence of modulation frequency for the PVDF thin films sensor

7. Conclusion

An electrical chopped frequency device was successfully made to characterize pyroelectric sensors. It was composed of a chopping system that includes an Arduino UNO programmed through a computer to generate multiple wavelength transmitting circuit to convert the wavelengths generated .to IR signals with the range of the chopping frequency. Sensing part with the amplification circuit was tested using an oscilloscope. The sensor was tested in the range from 0.01 Hz to 100 Hz. It was found that voltage responsivity for PVDF pyroelectric sensor equal to 117 V/W at 0.5 Hz, NEP was about 4.42×10^{-7} W/Hz$^{1/2}$ and detectivity was about 1.12×10^{6} at 100 Hz.

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