Journal of Applied Sciences and Nanotechnology, Vol. 3, No. 2 (2023)

Journal of Applied Sciences and Nanotechnology

Journal homepage: jasn.uotechnology.edu.iq

A New Technique for Measuring Laser Pulse Energy Using PZT/SiO_2

[1]Mariam Mohamed Abud*, [2]Mohanad Mousa Azzawi, [1]Hawazen Fadhil Alnaqeeb

[1]Department of Physics, College of Education, Mustansiriyah University – Iraq

[2]Department of Optoelectrics and Laser, Material Research, Ministry of Science and Technology – Iraq

ARTICLE INFO

Article history:
Received: December, 30, 2022
Accepted: April, 05, 2023
Available online: June, 10, 2023

Keywords:
Laser pulse Energy,
Lead zirconate titanate (PZT),
Joulemeter,
Piezoelectric Effect

Corresponding Author:
Mariam Mohamed Abud
marmoh_1968@uomustansiriyah.edu.iq

ABSTRACT

This paper introduces an innovative method for measuring laser pulse energy using photoacoustic converters. The concept of paper design and built energy meters using PZT as three specimens have a diameter of (20, 24, and 25) mm, and coating SiO_2 was chosen in this test because it has unique properties, is affordable and is compact. Genetic energy meters are expensive. They were comparing the genetic meter (used in this study that is manufactured of pyroelectric material and PZT/SiO_2). The outcomes demonstrated that within the laser pulse's energy (100-400mJ). Peak voltage values for PZT composites range from 0.48 to 0.84 volts at the voltage output as their diameter increases (PZT-S with a diameter of 20 mm). The output voltage ranges for PZT-M (diameter 24 mm) and PZT-B (diameter 25 mm) are 0.18 to 0.68 and 0.08 to 0.56, respectively. The design has been built and characterized by measured voltage and energy meter sources. A piezoelectric actuator had been fabricated on silicon sand wafer composites by converting the light waves (the laser pulse) into shock waves. Unlike the energy meter type (pyroelectric) for genetic-, the energy meter created in (PZT/SiO_2) is unaffected by Damage caused by high temperatures from laser Nd: YAG pulse energy.

https://doi.org/10.53293/jasn.2023.6122.1197, Department of Applied Sciences, University of Technology - Iraq.

1. Introduction

The modern world needs a lot of electricity to increase production, yet conventional energy sources are continually running out due to unsustainable energy use [1-3]. By using varied pulse energies of an Nd: YAG laser during pulsed laser deposition, thin cadmium oxide: nickel oxide (CdO: NiO) films were created. And low-power electronic devices. [4-18]. The lower the price of photovoltaic systems, the more solar concentrators were used [19]. The two types of materials that are most frequently employed in producing piezoelectric materials are as follows: The single crystal is a kind of quartz crystal (SiO_2) [20-22]. The photo-electrochemical etching (PECE) method was used to create nanocrystalline porous silicon (PSi) [23]. The second is called polycrystalline materials, Lead zirconate titanate (PZT), and barium tantalite ($BaTiO_3$) [24]. Barium titanate is a widely used substance in electric ceramics and microelectronics domains because of its outstanding properties [25]. The majority of these applications—which include piezoelectric sensors, ultrasonic transducers [26], and filters—rely on barium titanate's ferroelectric behavior, Polyvinylidene Violet (PVDF) [26, 27]. The research endeavour aims to design and construct a piezoelectric PZT with sand ($SiO2$) composite as an acoustic sensor with a low-cost, high-energy generator utilizing an Nd: YAG pulse laser.

2. Theoretical concept

Piezoelectricity, a typical physical phenomenon, is derived from the Greek word piezein, which means to apply pressure [28], Charge imbalance within primitive unit cells, which leads to the production of a net electric dipole, explains the physical genesis of piezoelectricity [29]. Utilizing piezoelectric technology, piezoelectric sensors detect the energy generated by the pressure of the strike of photons of a pulse laser and convert it into an electric charge using a piezoelectric lead titanium transducer (PZT) as a source of energy generation. There are two types of the piezoelectric effect: the direct impact, which describes how a material may convert mechanical strain into electrical charge, and the inverse effect, which describes how a material can convert an applied electrical potential into mechanical strain energy. Many different types of natural and artificial materials, including single crystal materials, piezoelectric ceramics [30], piezoelectric polymers [31], piezoelectric composites [32-34], and piezoelectric thin films, display the phenomena of the piezoelectric effect. Two examples of the many different types of piezoelectric materials are piezoelectric ceramics and piezoelectric composites. The work of this crystal is based on converting the laser energy falling on it into mechanical stresses that cause the generation of an electric charge. When the pressure is applied to the electrodes of the crystal, it will lead to mechanical deformation of the crystal and thus to the generation of an electric charge. The piezoelectric microphone best illustrates this phenomenon, and phonographs transform sound vibrations into pressure and subsequently into an electric potential difference [35]. Electrical energy is stored as an electric field in the piezoelectric components. The material's capacity to convert mechanical strain into electrical charge is called the direct piezoelectric effect [36]. The principle of piezoelectric generators is shown in Fig. 1.

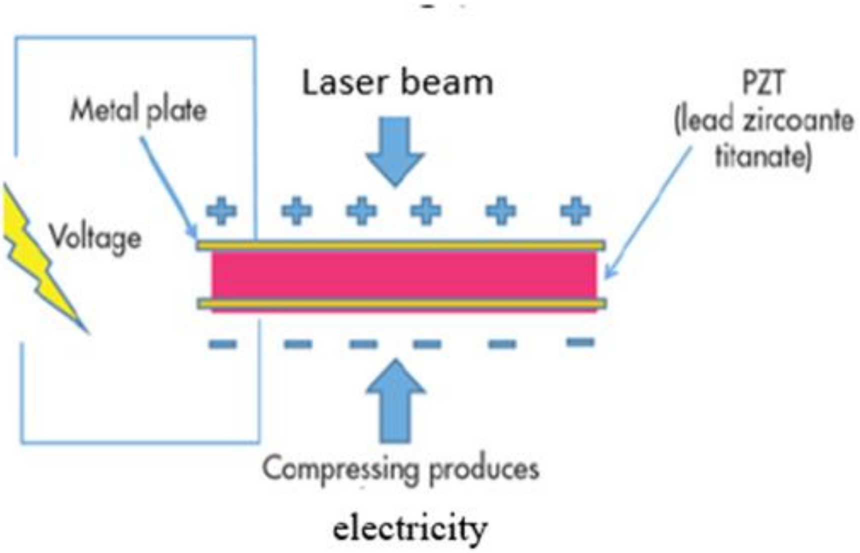

Figure 1: PZT crystal through the phenomenon of piezoelectricity,

When Pin, the incident power of the laser, can be computed by multiplying the sensor area (A) in square meters by the (I) laser irradiance in (W/m^2) is given by Eq. (1) [37]:

$$\boldsymbol{P_{in} = I \times A} \qquad (1)$$

Two mechanical and two electrical variables are present in this Eq. (2) and (3). The following equations can be used to determine the direct Piezoelectric effect and the Converse Piezoelectric effect [38].

Direct Piezoelectric Effect: $$\boldsymbol{D_v = d.\sigma + \varepsilon^T.E} \qquad (2)$$

Converse Piezoelectric Effect: $$\boldsymbol{S_v = s^E.\sigma.E} \qquad (3)$$

Where S_v is the strain vector, d is the piezoelectric constant matrix, Dv is the electric displacement vector, σ is the stress vector, $\varepsilon^T$is the dielectric permittivity matrix at constant mechanical stress, the matrix of compliance coefficients at constant electric field strength, and E is the electric field vector. The subscript t denotes the matrix transposition. Different piezoelectric coefficients, such as the dielectric coefficient (ε_{ixy}), the piezoelectric charge constant (d_{xy}, and the piezoelectric voltage constant, have different physical meanings (g_{xy}); due to an applied electric field in the j-axis, the dielectric coefficient (ε_r) establishes the charge per unit area in the r-axis. When a piezoelectric material has capacitance C, thickness d, and an electrode area A, the relative dielectric constant (r) is given by Eq. (4) [39]:

$$\boldsymbol{\varepsilon_r = \frac{C*A}{\varepsilon_0 d}} \tag{4}$$

where ε_0 is the permittivity of free space = 8.854 x 10^{-12} F/m. n sensor applications. The piezoelectric voltage constant, the direct piezoelectric effect, is the underlying theory behind how energy is converted in a piezoelectric material. Creating a parallel plate capacitor, upon which a charge is applied from an external power source, is the foundation of electrostatic conversion. By altering the capacitor layout (plate overlap area or plate separation), the voltage and/or charge on the capacitor changes. A parallel plate capacitor with plate area A and plate spacing d has a capacitance of about [40]:

$$\boldsymbol{C = \varepsilon\frac{A}{d} = \frac{Q}{V}} \tag{5}$$

Where ε is the dielectric constant of the insulating material between the plates, and Q and V are the charge and the voltage on the capacitor, respectively. The energy stored in the capacitor is [41]:

$$\boldsymbol{E = \frac{1}{2}QV} \tag{6}$$

If the charge is held constant, then combining Eq. (5) and Eq. (6), the energy becomes in Eq. (7):

$$\boldsymbol{E = \frac{Q^2 d}{2\varepsilon A}} \tag{7}$$

If the voltage is constrained, the energy becomes a linear piezoelectric material employed as a sensor and actuator Eq. (8):

$$\boldsymbol{E = \frac{\varepsilon A V^2}{2d}} \tag{8}$$

Based on the concepts mentioned previously, it is possible to take advantage of the phenomenon of converting energy (pressure) into an electrical signal (voltage), where the laser pulse is the incident energy, which in turn generates force, pressure, or vibration on the surface of the crystal, as the laser pulse has photon energy absorbed from Before the crystal (PZT), In direct proportion to the rise in incoming laser power, an electric signal (voltage) is produced. Assume that every pulse contains the same amount of energy, E. Power is merely the rate of change in the energy flow over time (energy per unit time(T). and power or energy meters when working with laser pulses and power or energy meters [42] Eq. (9):

$$\boldsymbol{P_{ave} \times T = E} \tag{9}$$

3. Experimental Procedure

Three specimens (1, 2, and 3) of the type (PZT) with different diameters (20, 24, and 25) mm, respectively, were prepared and studied from local markets without coating. Three specimens (1, 2, and 3) of the type (PZT) with different diameters (20, 24, and 25) mm, respectively, were prepared and studied from local markets without coating. As the laser pulse absorbs photon energy from before the crystal (PZT), an electric signal (voltage) is generated directly proportional to the increase in the incident laser power. The laser pulse is the incident energy which generates force, pressure, or vibration on the surface of the crystal. The three types of composites prepared and adhesive are grain sand (SiO_2) with size particles 100 µm by epoxy and resin with a substrate plate for each PZT crystal surface with different diameters 20, 24, and 25 mm, as shown in Fig. 2.

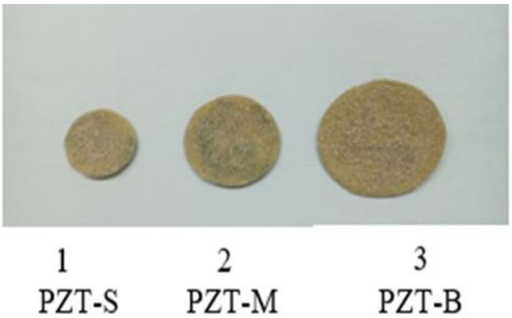

Figure 2: The PZT composites prepared and adhesive their grain sand (SiO_2), the diameters (1-20mm), (2-24 mm), and (3-25 mm).

The specimens were installed inside Circular aluminium containers that protect the crystal from external influences and fix the crystal on it, as in Fig. 3.

Figure 3: Explain the samples prepared to test with the coating silicon sand (SiO_2).

The setup of calibration contained a laser Nd: YAG with wavelength 1064 and 532nm is the well-suited range in red and green colour, and its type (HF-301 Q-Switched ND YAG with wavelength 1064nm laser can penetrate a deep layer with a repetition from 1 Hz, with this INTEGRA version of our well-liked QE25LP-S-MB pyroelectric-based energy detector. Connect it to your computer and download our free program with PC- Genetec-EO, Mastro touch screen display for energy measurements. It is plugged into the PC, and our free software, PC- Genetec-EO material, is installed as a source of energy generation. A laser source and genetic-type Maestro detector were placed at a distance of 37 cm to measure the laser energy pulse. The setup is shown in Fig. 4.

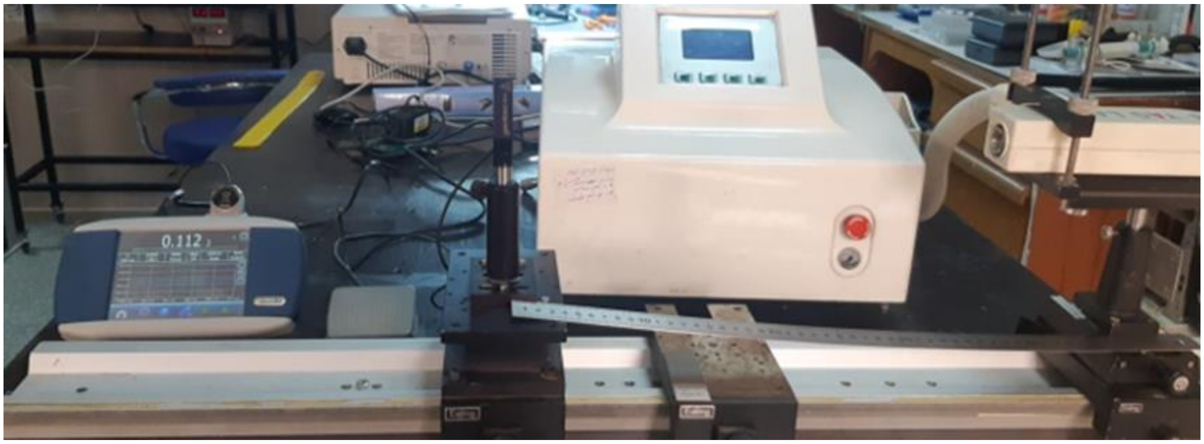

Figure 4: set up of Standard Energy pulse for Nd: YAG source laser and joulemeter type genetic-ϵ.

4. Results and Discussion

To gauge laser energy and test out this integrated laser energy meter. You may measure energy up to 1J with a maximum energy of 0.529 J/cm^2.The Scale of energy of radiation pulse (280 -1000) mJ for pulse duration 10 ns for laser Nd: YAG with wavelength 1.64 µm. The statistics in Table 1 show that the apparatus in Fig. 4 was calibrated to locate and measure the laser energy accurately and dependably while measuring the specimens.

Table 1: A genetic joulemeter (QE25LP-S-MB) was employed in conjunction with pulsed laser energy (Nd: YAG = 1.064 m) for calibrated

Nd: YAG system (mJ)	genetic-ϵ joulemeter (mJ)
280	95
300	140
400	180
500	225
600	250
700	335
800	410
900	450
1000	509

Fig. 5 illustrates the relationship of the energy sensor for the preferred QE25LP-S-MB (made in Canada) pyroelectric-based energy detector using a laser source and genetic detector at a distance of 37 cm. Bielecki et al.'s calibrations of the YAG energy pulse radiation reveal that the produced energy meter is distinguished by an extreme linearity of indication in this assumed large range up to 100 mJ [42]. According to the findings, the measured energy value for genetic type (QE25LP-S-MB) is only around half (~0.554) as high as the energy of Nd: YAG pulse (mJ).

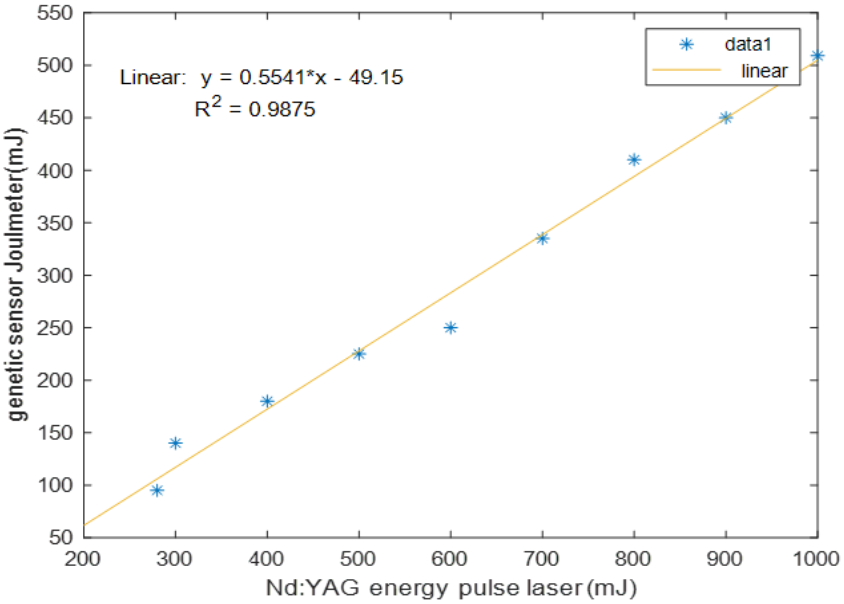

Figure 5: shows the energy measured sensor's dependence on the designed-on energy Nd: YAG pulse measured with a standard meter.

Three PZT composites with diameters of 20, 24, and 25 mm were subjected to the experiments, which the following symbols represent (1. PZT-S, 2. PZT-M,3. PZT-B) as shown in Fig, 2. The response of this specimen was poor (3. PZT-B) as a result of the large diameter and low sensitivity or response to the incident laser pulse when a laser pulse was recorded at a distance of 37 cm using the PZT /SiO_2 composite as shown in Fig, 6, and given the voltage signal for experimental specimens, the oscilloscope was used to capture the data in Fig, 7.

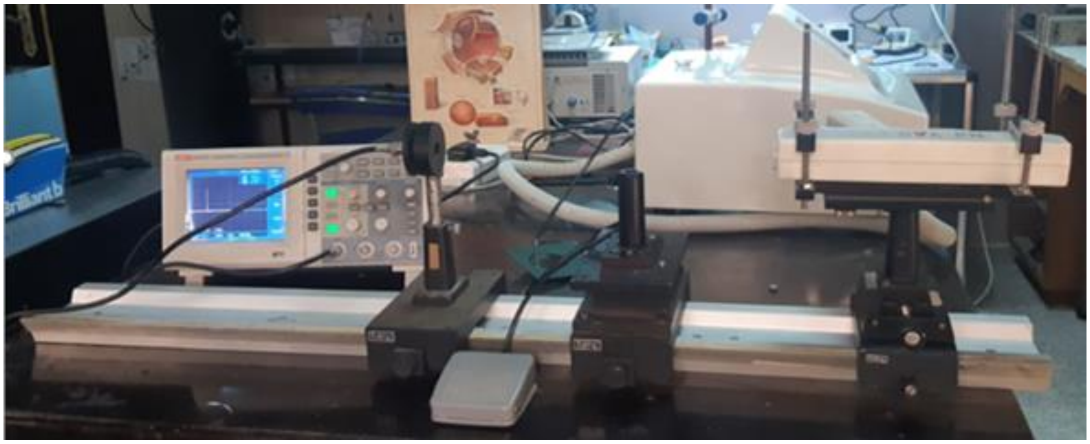

Figure 6: set up of test PZT composite with SiO_2 sand have different diameters.

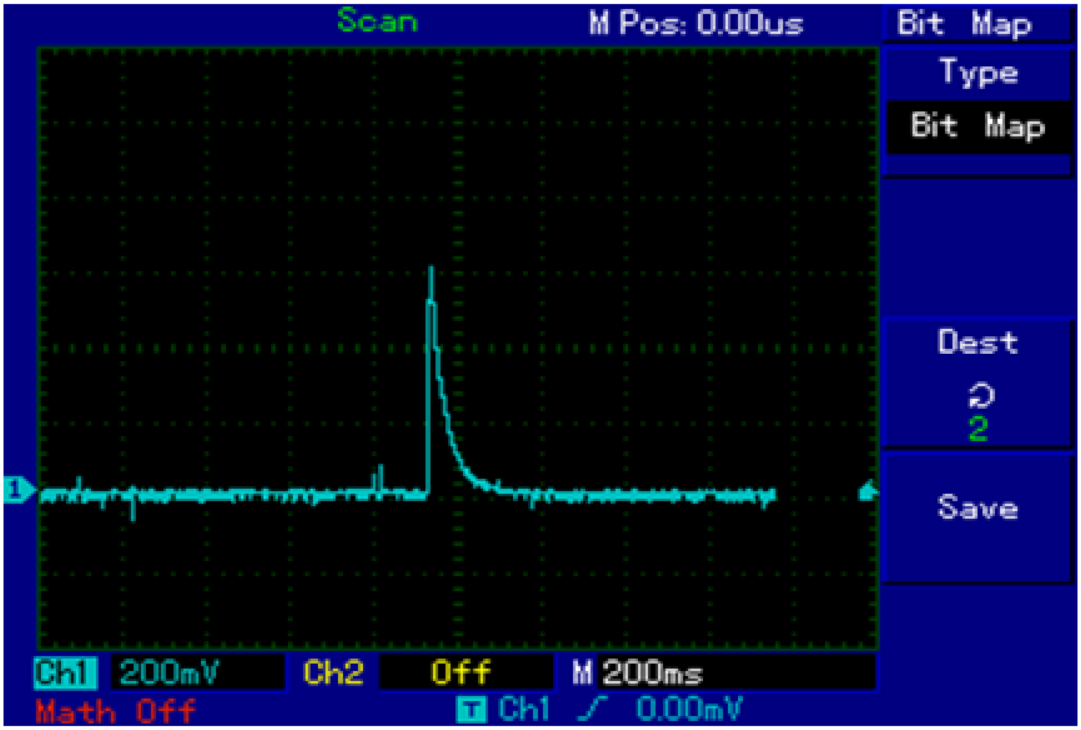

Figure 7: represents the pulse of laser energy for specimens (PZT/SiO_2) composite recorded from an oscilloscope.

Table 2 and Fig 8 show the data for specimens from either the voltage calculations or the Nd: YAG energies pulse standard. The initial sample (PZT-S): The rate of Excellent response of a laser pulse recorded at the same distance was more than the value calculated in the pulse laser, and equation 8 states that the resulting voltages are precisely proportional to the size of the resulting energy. These findings concur with those of Canon et al., who proposed that the crucial mechanical to electrical conversion processes in these types of devices and systems, together with important design factors, experimentally proven mechanical in the choosing of optimal layouts and materials and development of a piezoelectric PZT-based sensor [43]. In the whole range of energies, the relationship between the energy of the laser pulse and the peak value at the voltage output is linear (100-400mJ). The peak voltage value of PZT composites falls as their diameter grows. A 10-ns laser standard pulse has a 400 mJ maximum energy. The calibration's findings show that the developed energy meter has very high linearity across the board for all PZT composites and a wide range of variation in laser energy pulse (100-400mJ).

Table 2: Nd: YAG pulse energy meter standard (mJ) and output voltage for different specimens.

Nd: YAG pulse energy meter standard (mJ)	**The voltage of the PZT-S specimen (mV)**	**The voltage of the PZT-M specimen (mV)**	**The voltage of the PZT-B specimen (mV)**
100	480	180	80
150	540	220	120
200	600	300	160
250	660	400	320
300	720	520	360
350	800	560	440
400	840	680	560

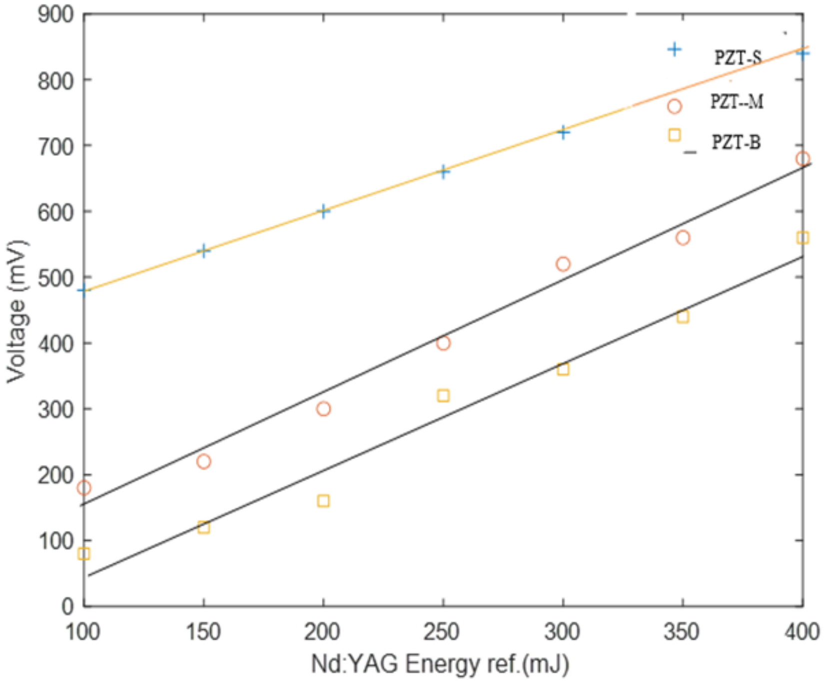

Figure 8: the output voltage signal's reliance on the Nd: YAG energy standard pulse for various PZT composite diameters.

5. Conclusions

In this paper, the new energy meter uses a piezoelectric crystal (PZT) as a sensor that deals with the incident photon's energy as a mechanical pressure energy meter. In contrast, the genetic energy meter uses a crystal (pyroelectric material). The ultimate accomplishment was the creation of a laser pulse energy meter utilizing a PZT/SiO_2 composite as a sensor that deals with the energy of the incident photon according to a voltage signal created. Novel materials used in the manufacture of the energy meter are very cheap compared to the genetic meter and are very expensive. These PZT/SiO_2 composites can be dealt with in different forms according to the need, and quite quickly, unlike the energy meter type genetic, the energy meter made in (PZT/SiO_2) is not damaged when exposed to laser pulse energy. (1) simplicity (2). Fuel transportation is not a concern. (3) Cheap (4). Very simple to keep up. (5), Easy to control, (6). Lowers the price of labour, (7). Low energy usage (8) Year-round access to energy and development of the economy.

Acknowledgement
We take this opportunity to express our gratitude to Hussein Mohanned, the researcher, and Dr. Haideer Al-Jobori, the Department of Optoelectronic and Laser, and the Ministry of Science and Technology.

Conflict of Interest
The authors declare that they have no conflict of interest.

References

[1] V.R. Priyanka, K.S. Bhagyashree, K. P. Mahure, Power generation using PZT for the auto street lighting system, International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056 Vol. 5, no. 12, 2018.
[2] F. Hussein, H. Alaa., H. Shneishil," Effect of Solar Cell Temperature on The Performance of Compound Parabolic Solar PV Concentrator", Journal of Physics: Conference Series **2322** (2022) 012087, IOP Publishing.
[3] J. Zhang, .; M. Lin, W. Zhou,T. Luo, L. Qin, Modeling of a Rope-Driven Piezoelectric Vibration Energy Harvester for Low-Frequency and Wideband Energy Harvesting. Micromachines, 12, 305, 2021.
[4] Kh. D. Mahmood, K. A. Aadim , M. G. Hammed , Effect ofthe Pulsed Laser Energy on theProperties of CdO: NiOComposite Thin Films for Solar Cell Applications ,Iraqi Journal of Science, Vol. 63, No. 3, pp. 1004-1017, 2022.
[5] P. Aceti ,M.Rosso , R.Ardito ,N.Pienazza , A. Nastro ,M.Baù ,M.Ferrari ,M.Rouvala ,V.,A. Corigliano „" Optimization of an Impact-Based Frequency Up-Converted Piezoelectric Vibration Energy Harvester for Wearable Devices. **Sensors (Basel, Switzerland)**, vol. 3, no. 23, pp. 139, 2023.
[6] O. Kanoun "Energy harvesting for wireless sensor networks (Berlin, Boston: De Gruyter Oldenbourg), 2018.
[7] G. Clementi, F.Cottone, A. D. Michele, L. Gammaitoni, M. Mattarelli, G.Perna, Miquel L.Suárez, S. Baglio, C. Trigona, I. Neri, Review on Innovative Piezoelectric Materials for Mechanical Energy Harvesting, Energies, Vol 15, no. 6227, p 6227 , 2022.
[8] F. K. Shaikh and S.Zeadally ," Energy harvesting in wireless sensor networks: A comprehensive review Renew. Sustain. Energy Rev. 55 1041–54, 2016.
[9] L. Pan ,L.Cheng ,P.Suhas, J . Veetil ,Z.Jianqiang ,Temporal self-referencing technique for the diagnostics of nanosecond laser pulse,Optics and Lasers in Engineering, Vol. 148, pp. 106751, 2022.
[10] P. D.Frischmann K, Mahata and F. Würthner," Powering the future of molecular artificial photosynthesis with light-harvesting metal supramolecular dye assemblies Chem. Soc. Rev. 42 1847–70, 2013.
[11] J.Radziejewska, ;M.Strzelec, ;R.Ostrowski, ;A.Sarzyński, Experimental investigation of shock wave pressure induced by a ns laser pulse under varying confined regimes, Optics and Lasers in Engineering, vol. 22, no. 126 pp. 10591, 2020.
[12] M.Seyedmahmoudian , T. K. Soon ,E. Jamei, G. Sidarth Thirunavukkarasu, B. Horan, S. Mekhilef and A. Stojcevski "Maximum power point tracking for photovoltaic systems under partial shading conditions using bat algorithm Sustainability 10 1347, 2018.
[13] A. A.F.Husain,W. H. Zuha ,W.S.Shafie, N.H.Mohd, Sh. S. Pandey," A review of transparent solar photovoltaic technologies Renew. Sustain. Energy Rev. 94,779–91,2018.
[14] C.H.Ng, H.N.Lim,S.Hayase, Z.Zainal, N.M.Huang, "Photovoltaic performances of mono-and mixed-halide structures for perovskite solar cell: A review Renew". Sustain. Energy Rev. 90 248–74, 2018.
[15] M.M.H.Shuvo, T. Titirsha, N. Amin, S.K. Islam, "Energy Harvesting in Implantable and Wearable Medical Devices for Enduring Precision Healthcare". Energies, 15, 7495, 2022.

[16] Y.Zhang , Ph.Th.Thuy Phuong , E. Roake , H. Khanbareh , Y. Wang , S. Dunn , C.s Bowen "Thermal Energy Harvesting Using Pyroelectric-Electrochemical Coupling in Ferroelectric Materials",Joule, Vol. 4, no. 2, pp. 301-309, 2020.

[17] D.Balaya, D.Palani, X. Naresh, . X.Sheng ," Energy Harvesting and Storage: Materials, Devices, and Applications XII, SPIE Defense, Security, and Sensing,Proc. SPIE Conference Volume, 2022.

[18] M. G. JIMÉNEZ," Ultrasonic pulse generation by a piezoelectric transducer at cryogenic temperatures" MD thesis of Physics, UNIVERSITAT POLITÈCNICA DE CATALUNYA,2018.

[19] S.H.Alaa, J.E. Mahdi, A.H. Mohammed," Comparison between point and linear focus Fresnel lenses PV solar concentrator", AIP Conference Proceedings 2372, 170001, 2021.

[20] S.Ersoy, T. Waqar, in Reference Module in Biomedical Sciences, 2022, Acoustic Wave Conductometric Sensors, Encyclopedia of Sensors and Biosensors,Vol. 3, pp. 591-616, 2023.

[21] M. Mohammed Al-shboul, low Wind Profile energy harvester using Rotor and Piezoelectric, circuit. Microsystem Technologies, 17(5-7), pp. 1025-1036. *Phillips*, 2017.

[22] F. Chen, M. Zhang, Ch.H. Yang, Application of ultrasound technology in processing of ready-to-eat fresh food: A review, Ultrasonics Sonochemistry, Vol. 63, 2020.

[23] A.H.Hasan ,. R.A. Ismail," Preparation and Characteristics Study of High-Quantum Efficiency Ni/Psi/c-Si and cd/Psi/c-Si Double-Junction Photodetectors", Springer Nature BV 2022.

[24] Gh. S. Jassim, M. M. Najim, W. M.Salih, Preparation of Micro Barium Titanate Powder and Comparison with Nano Powder Properties, Journal of Applied Sciences and Nanotechnology, Vol. 1, no. 4, 2021.

[25] A. K. Esraa, "Experimental design systems to produce electricity from speed," Ph.D., Institute of Materials Science, University of Technology, Electromechanical Engineering Department, 2016.

[26] A. Abbas, Application of piezoelectric materials in smart roads and MEMS, PMPG power generation with transverse mode thin film PZT, International Journal of Electrical and Computer Engineering, vol. 6, no. 3, pp. 857-

[27] A.Saad, A.Tuama, A.O. Abdulrazzaq, K.A.Shaima K., F.Noora," Investigating the Impact of Tilt Angle, Orientation, and Configuration on PV System Performance Using PVSyst Software", Journal of Applied Sciences and Nanotechnology, Vol. 1, No. 3, 2021.

[28] Sh.Kim HS, J.K. Kim, A review of piezoelectric energy harvesting based on vibration, International journal of precision engineering and manufacturing, 12 (6), 1129-1141, 2011.862,201.

[29] B. Jaffe, W. R. Cook Jr, and H. Jaffe, *Piezoelectric ceramics* vol. 3: Elsevier, 2012.

[30] H.H.Singh, , S. Singh, and N. Khare, Design of flexible PVDF/$NaNbO_3$/RGO nanogenerator and understanding the role of nanofillers in the output voltage signal. Composites Science and Technology, 149: p. 127-133, 2017.

[31] *Piezoelectric Ceramics: Principles and Applications*: APC International Ltd., 2011.

[32] E. Carvalho, L. Fernandes, C. M. Costa1, S. Lanceros-Méndez," Piezoelectric polymer composites for sensors and actuators,2020.

[33] H. Fang, Introduction. In: Novel Devices Based on Relaxor Ferroelectric PMN-PT Single Crystals. Springer Theses. Springer, Singapore. 2020.

[34] E. Fukada, "History and recent progress in piezoelectric polymers," *Ultrasonics, Ferroelectrics, and Frequency Control, IEEE Transactions on,* vol. 47, pp. 1277-1290, 2000.

[35] M.Habib, and K. Hornbostel "A review of ceramic, polymer and composite piezoelectric" J ournal of Physics D: Applied Physics, vol. 55, no. 42, 2022.

[36] S. R. Moheimani and A. J. Fleming, *Piezoelectric transducers for vibration control and damping*: ,Springer, 2006.

[37] Sh.Z. Faten, A.H. Ali, S.K. Ghada, "Improving the Performance Efficiency of Solar Panels by Using Flat Mirror Concentrator Fat ", AIP Conference Proceedings 2190, 020054 (2019).

[38] E. Minazara, D. Vasic, and F. Costa," Piezoelectric Generator Harvesting Bike Vibrations Energy to Supply Portable Devices", RE&PQJ, Vol. 1, No.6, March 2008.

[39] SH.K.Amal," Exploration of Non-MPB PZT Compositions for High Piezoelectric Voltage Sensitive 0-3 Composites"," MD, Institute of Aerospace Engineering Delft University of Technology, 2014.

[40] I. Chilibon," Influence of Structure Configuration on Strained Devices: A Piezoelectric-oriented survey, SENSORDEVICES: The Seventh International Conference on Sensor Device Technologies and Applications, ISBN: 978-1-61208-494-7 29,2016.

[41] I. Chilibon, Piezoelectric Structures and Low Power Generation Devices, *Sensors & Transducers, Vol. 205, Issue 10, October 2016, pp. 16-24*.

[42] C. Covaci &A.Gontean, Piezoelectric Energy Harvesting Solutions: A Review, Sensors 2020, 20, 3512.

[43] C. Dagdevirena, , J.Pauline , L. O.Tuzmanc , K.Park , J.L.Keon, Y. Shi , Y. Huang , A.J. Rogers , "Recent progress in flexible and stretchable piezoelectric devices for mechanical energy harvesting, sensing and actuation ",Extreme Mechanics Letters,Volume 9, Part 1, December 2016, PP. 269-281.