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Investigations on the triboelectric electricity generation and its application in energizing a voltage driven display device

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ABSTRACT

We report the results based on generation of electrical energy by means of triboelectric effect. Various combinations of the polymers have been investigated in their bulk form for their triboelectric generation capabilities. The combination of polyvinyl chloride and acrylic polymers were found to be suitable for triboelectric generation with voltage ~ 5V and charge ~ 150nC being generated. Further, different dimensions with varying area of contact of the said polymers combination were used to observe switching behavior of a ferroelectric liquid crystal (FLC) sample cell. Based on the above observations it is proposed that sufficient electrical energy may be generated by harvesting contact electrification to energize not only LC based display devices but also current controlled devices, such as light emitting diodes, by employing suitable integrating technique.

Keywords: Liquid crystals, Liquid crystal displays, Optical transmission, Polymers, Triboelectric effect.

INTRODUCTION

The generation of electric power by means of non-conventional and renewable sources of energy has long been appreciated. In today"s scenario with conventional energy resources (fossil fuels) fast depleting, the techniques/methods that extract power from non-conventional and renewable sources are keenly being investigated. Solar cells and windmills are promising examples of methods to generate electric power from natural sources. However, such techniques require huge investment, sophisticated fabrication methods (in case of solar cells) and are deployable in selective regions (for wind energy). With this background, an ancient and well-known phenomenon, *i.e.* generation of electric charge by rubbing two polymers with different physical and chemical properties could be of great interest. This "contact electrification phenomenon" of energy generation is known as triboelectric effect in literature. Triboelectric effect is the phenomenon of charge generation by rubbing two materials of different work functions. In this phenomenon, the surface of one material attracts some of the electrons from that of the other and becomes negatively charged and in turn the other material becomes positively charged when they are separated [1, 2]. The magnitude of the charge generated in such a technique is very small and the recombination of the generated charges (through the external load) results in a small current (transient) [3, 4]. The integration of such triboelectric currents to effectively energize the low power current controlled devices requires advanced and sophisticated methodology.

On the other hand, voltage generated by triboelectric effect may be utilized to switch on the voltage controlled optical devices based on liquid crystal (LC) materials [5]. LCs are the delicate phases of matter, which possess the properties of a solid (dielectric and optical anisotropy) as well as that of a liquid (fluidity) simultaneously [6]. The LC molecules are very sensitive to external electric field due to dielectric anisotropy. The orientation of these molecules may be modulated easily by applying small voltages and hence controlling the associated optical properties. This property of LC can be used in display and non-display applications. The above said phenomenon is obtained by sandwiching them suitably in few micron thick sample cells under certain conditions (prior alignment treatment to the glass plates of the sample cell) [7]. That is why almost 80 % of today"s display devices are based on such materials. It has been found that the LC sample cells could be energized by tribo-electrically generated voltage [5]. While studying the switching of LC samples, it was found that the charge generation capability by triboelectric effect strongly depends on the nature of polymers, strength of rubbing, area of contact and certain other parameters [8]. Keeping in mind these facts, we have investigated the charge/voltage generation capabilities for a number of polymer combinations in their bulk form only by taking into account their properties, area of contact etc. Based on our observation, we selected a combination of polymers, which is optimal for triboelectric generation capability.

In the present paper, we report and discuss results based on triboelectric behavior of certain combinations of polymers in their bulk form. Further, switching behavior of a ferroelectric LC (FLC) material by using triboelectric effect has been demonstrated. It is proposed that sufficient electrical energy may be generated by harvesting contact electrification, which can energize not only LC based display devices but also current controlled devices such as light emitting diodes (LEDs) by designing a proper circuitry.

METHODOLOGY

Different polymers such as polyvinyl chloride (PVC), acrylic, Teflon, silicon rubber *etc.* were purchased in the form of cylindrical cladding of varying area of cross sections with conducting (copper) cores of length 1 meter long. We used the same schematics for the measurements that were used in an earlier report [5]. The rubbing area *i.e.* area of contact for all the specimens (which were used in the form of claddings of conducting wires) was chosen to be constant with a value ~ 0.5 x 20 cm^2. For measurements of generated voltage, the copper cores were connected with one of the electrodes of a suitable capacitor and its other electrode was grounded. Rubbing was performed on the cylindrical (curved) surface of the wire with another polymer. The generated voltage was measured across the capacitor by using „Fluke‟ make multimeter.

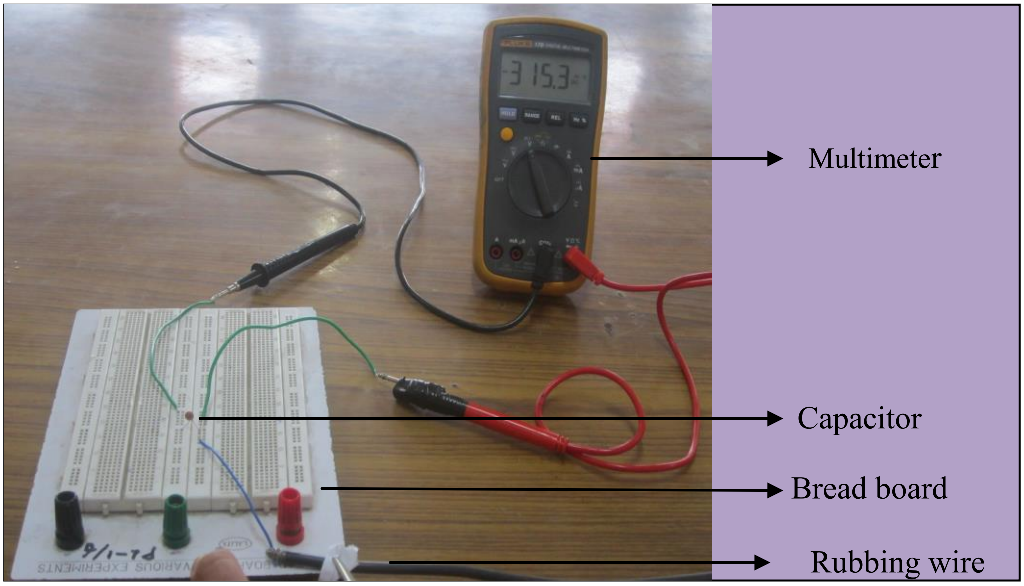

Figure-I: Photograph showing the simplified set up for measurement of tribo-electrically generated voltage.

Figure-I shows the simplified set up for measuring tribo-electrically generated voltage. LC sample cells were fabricated by assembling indium tin oxide (ITO) coated glass substrates. The desired (squared) electrode pattern (4.5 x 4.5 mm^2) was obtained using photolithography technique. Uniform spacing between two substrates has been maintained by Mylar spacers of thickness 6 μm. FLC material (LAHS 19) was filled in the LC sample cell at temperature well above its isotropic transition temperature. Optical polarizing microscope (Axioscope-40, Carl Zeiss, Germany) and electrometer (Keithley-6514, programmable electrometer, U.S.A.) have been utilized for electro-optical, charge, and voltage measurements, respectively.

RESULTS

To take experimental observations, we performed the rubbing by hand and pencil shaped specimens coated with acrylic and asbestos on 1 meter long conducting wires having different kinds of claddings on it as well as different diameters. As discussed in methodology section, the tribo-electrically generated voltage has been measured as the potential difference between the two plates of the capacitor.

It has been found that the magnitude and sign of the generated voltage strongly depends on the nature of the polymers, contact area, rubbing strength etc. The combination of silicon rubber rubbed by human hand is found to be one of the most efficient combinations amongst all considered to generate remarkable values of charge and voltage for almost fixed rubbing parameters [8]. Figure-II (a) shows variation of the charge generated due to rubbing (continuous with frequency ~ 1 Hz) of silicon rubber by human hand and asbestos respectively. In Figure-II (b) is shown the comparison of variation of charge generated when sample is rubbed with human hands continuously and with an interval of 10 seconds. We also measured the corresponding voltage and found maximum value ~ 0.7 V for combination of silicon rubber and human hand.

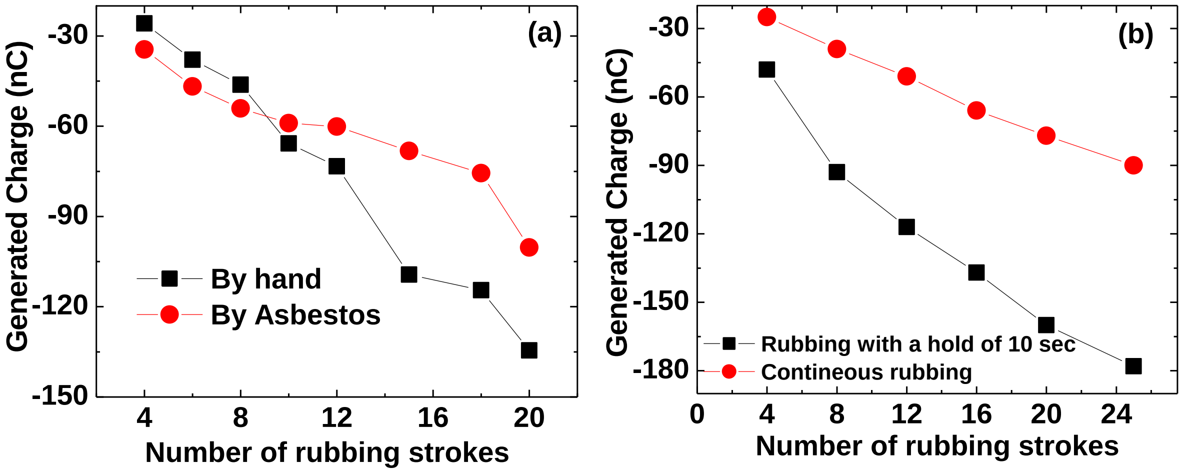

Figure-II Variation of generated charge when (a) Silicon rubber is rubbed by human hand and asbestos (b) Silicon rubber is rubbed (with hold) by human hand.

Figure-III shows the variation of charge generated using combination of PVC and acrylic for different contact areas. The contact area for rubbing was kept very small (~0.5 cm in width and 20 cm in length). Due to small contact area of polymers, the generated voltage is observed very small in magnitude (~ 1.5 V) for combination of PVC and acrylic. To study the effect of the same on their triboelectric generation capability, different dimensions of the polymers, acrylic and PVC, were used to fabricate triboelectric generator devices.

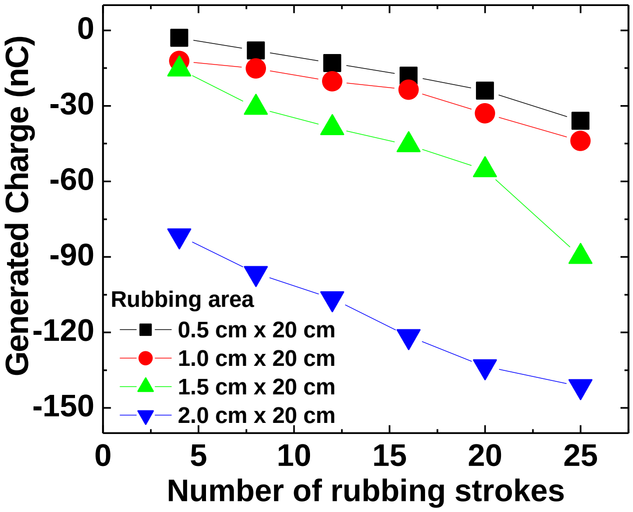

Figure-III Variation of charge generated with number of rubbing strokes for different areas of cross-section using combination of PVC and acrylic.

Figure-IV shows the electrical response of the triboelectric generator device. Conducting paste of silver was uniformly coated on the surfaces of sheets of polymers. Ohmic contacts were made on the conducting sides of the sheets to measure the voltage generated [inset of Figure-IV].

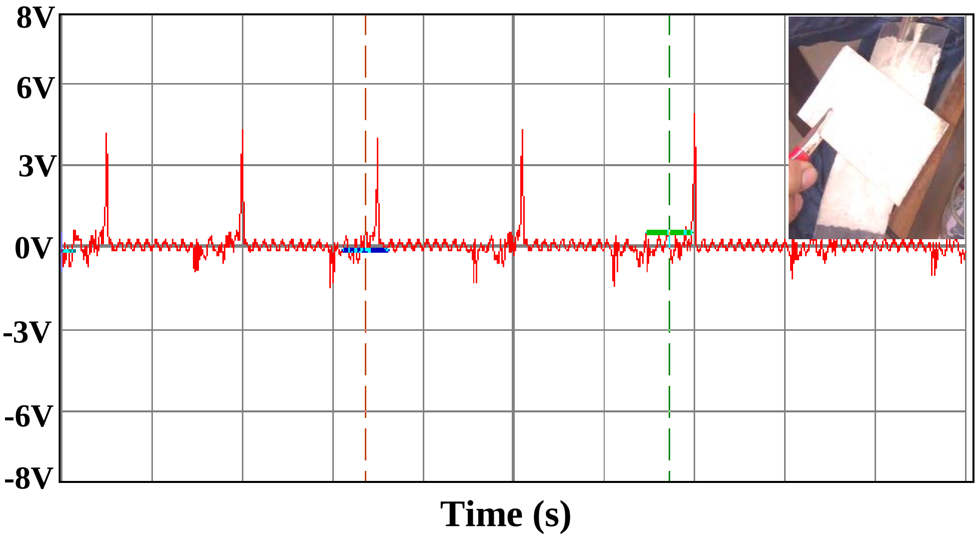

Figure-IV Electrical response of triboelectric device. Inset of the figure shows triboeletric generator device using thin sheets of PVC and acrylic.

The electrical response of fabricated devices has been recorded using a storage oscilloscope. The sharp peaks of voltage generated can easily be seen from the figure. Triboelectric generation was achieved by continuously touching and separating quickly the opposite surfaces of the polymers. This process was performed manually with a frequency of about 1 Hz. Further, we have checked the device performance for more than 200 cycles and found almost distortion free voltage generation performance. We observed generation of ~ 5 V for contact area of 9 x 5 cm^2 with sheet thickness of 0.5 mm PVC and 1 mm acrylic respectively. With such a significant value of voltage, few unit cells of LCD can easily be energized. To verify such kind of switching, we fabricated LC sample cell (thickness 6μm, area 4.5 x 4.5 mm^2) filled with FLC material LAHS 19. Figure-V shows the optical micrographs of original and switched state of FLC (LAHS 19) sample cell achieved by triboelectric generation.

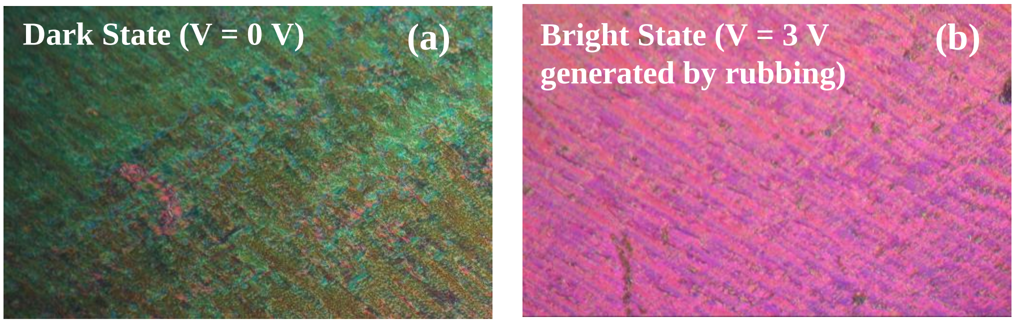

Figure-V Dark (a) and Bright (b) states of commercially known LAHS 19 FLC sample cell. The bright state of the cell is achieved by switching it by triboelectrically generated voltage.

To easily visualize the switching behavior of the FLC sample cell, we have recorded the change in its optical transmission intensity using a photodiode interfaced with the storage oscilloscope. Figure-VI shows the electro-optical switching response (variation of light transmission intensity with the rubbing strokes) of the same LCD cell.

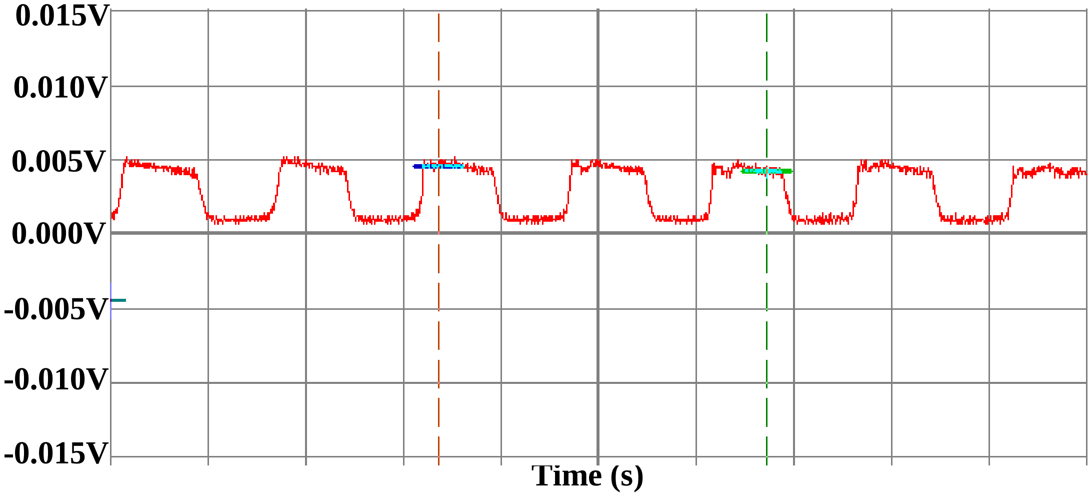

Figure-VI Optical response of a unit LC cell by triboelectric generation.

Further, to check the feasibility of harvesting the oscillatory motion in triboelectric generation, we utilized the to and fro motion of mass attached to a spring. We used here the elastic energy stored in the spring to rub the polymers. Figure VII shows the photograph of the set up used to harvest elastic energy to generate the voltage by triboelectric effect.

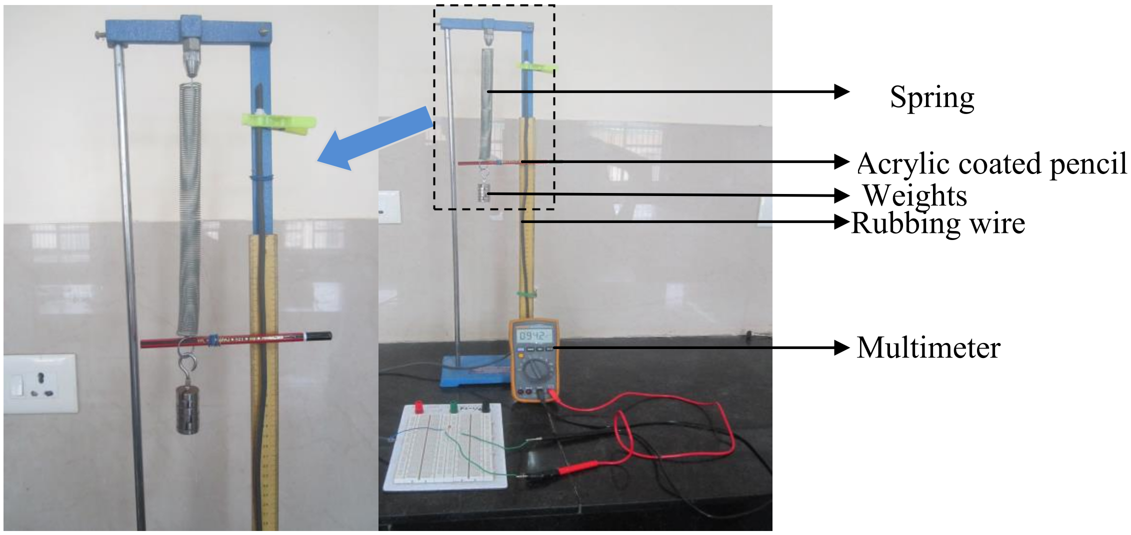

Figure-VII Photograph showing the triboelectric generation using motion of spring.

We attached a pencil coated with acrylic polymer suitably so that its surface is in contact with cladding (PVC) of a conducting wire of length 1 meter. The contact area between the polymers (*i.e.* PVC and acrylic) was kept very small (~0.5 mm in width and 10 cm in length) for obtaining sufficient numbers of oscillations of the mass attached to the spring. The mass was pulled down up to a distance such that the amplitude of first oscillation is approximately 10 cm and then suddenly released. The mass spring system made almost 20 oscillations (damped) before coming to rest and a fraction of the energy of the system is used in rubbing process to generate voltage. Due to weak (free) contact of pencil and PVC wire, the observed value of peak voltage generated is small in magnitude (~ 1.5 V). However, the system may be a clue to harvest natural oscillatory motion in generating electrical energy using triboelectric effect. We are in the process to modify this simple system with greater contact area and rubbing strength that will require additional periodic energy input to maintain the spring oscillations.

DISCUSSION

The current generation during the triboelectric effect is related to capacitance and voltage generated as

$$I = C\frac{\partial V}{\partial t} + V\frac{\partial C}{\partial t}$$

where C, V, t are capacitance, voltage, and time. Further, the voltage generated is dependent on the material parameters as

$$V = \pm \frac{2d.\sigma}{\varepsilon_o \varepsilon_r}$$

where d, σ, ε_o, ε_r, are the thickness of the polymer used, surface charge density, permittivity of free space, and relative dielectric constant of polymer respectively.

From the expression (above) it is clear that the electrical output generated by means of triboelectric effect is affected by the nature of materials used. Generally organic materials may be arranged in a table according to the amount of positive/negative charge generation capabilities that can be transferred in the form of triboelectric series [8]. It is analogous to the electrochemical series of materials that describes the tendency of a material to gain or lose electrons. The series lists materials from top to bottom in order of decreasing tendency to develop positive charge and increasing tendency to develop negative charge. Further, materials which are extremely apart (separated) in the series possess greater charge transfer capability when used in triboelectric generators. F.–R. Fan *et al* used the combination of Kapton-PET or PVC-PET and succeeded in achieving an output voltage of ~ 3 V with a power density of ~10 mW/cm^2 [10].

From Figure-II (a) it is clear that charge generated is greater when silicon rubber sample was rubbed by human hand. It has also been observed that the magnitude of the generated charge is greater when the rubbing was performed with a hold (Figure II (b)). In making such a hold during rubbing provides enough time to the generated charges to accumulate and hence generate greater magnitude of the same. It is worth mentioning here that the magnitude of the saturation value of generated charge/voltage has been found to vary from person to person (human hand). Besides the above combination, interesting results have been observed for the combination of PVC cladding (with higher diameter) rubbed by acrylic polymer.

One can conclude from Figure-III that magnitude of the voltage generated increases by increasing the contact area. It may also be concluded that the magnitude of the generated charge increases very sharply on increasing the rubbing contact area.

From Figure-IV it may be clearly seen that the magnitude of the voltage generated is almost 4 volts. The voltage generated using triboelectric effect for the combination of acrylic and PVC has been found to depend on the effective surface area of contact, contact strength, etc. With the values ~ 4-5 V of voltages generated, it is possible to switch and energize a few unit cells of LCD. LCD filled with FLC was used to study and verify such a switching process. FLC materials are basically composed of rod like organic molecules, which are special kind of LC materials as they exhibit ferro-electricty. LC molecules in ferroelectric phase are arranged in layers of helicoidal geometry in such a way that the molecular director rotates successively from layer to layer and always lies on a hypothetical cone with cone angle 2θ (where θ is the tilt angle) [9]. The symmetry (C_2) of FLC materials permits non-zero electric polarization associated with each FLC molecule perpendicular to the director. However, the net polarization of the material average out to be zero due to helix formation in absence of any external field. The helical unwinding takes place upon the application of external electric field as the polarization vectors try to align in the direction of applied field and in turn we have non-zero polarization of the FLC material. For observing a cumulative switching of all the molecules, we made surface treatment of the substrates prior to the assembling of the sample cell and this made all the FLC molecules to orient in a preferred direction. When such a sample cell is placed under the crossed polarizers and is rotated, the intensity of light transmitted through the sample becomes minimum and maximum two times each in a complete rotation. To observe switching, the sample is placed in the position of minimum intensity. Now, application of the electric field between electrodes of the sample cell causes switching of FLC molecules due to the coupling of electric field with that of the polarization vectors of the molecules leading to a change in the light transmission intensity (minimum to maximum).

From Figure-V, depicting electro-optical switching response, one can visualize the capability of modulating light intensity through LC sample cells, which is the basis of display devices based on such materials. As we showed that it is possible to energize unit LC cell using triboelectrc generation, we have further scope to utilize such technique to power display units based on LC materials.

From Figure-VI it is demonstrated that in the dark state of FLC cell, almost no light is allowed to transmit through the cell and we get minimum intensity corresponding to its dark state whereas maximum transmission of light takes place in its bright state. The switching happens due to the orientation motion of FLC molecules caused by the generated voltage across the sandwiching electrodes of the cell.

The interface mechanism of potentially active material is playing a very important role in stabilizing and recurrence of charge generation. For example the breaking and reformation of bonds at the interface and generation of induced charge at the opposite face in contact with electrodes during the process are the key functions. In case of polymers, the weaker bond formation like π-π and hydrogen bonding could have fast response process due to which the repetition of charge generation may have been possible. In the above selected materials, this key feature might have been highly influential factors. We selected different types of polymer materials for the study such as silicon rubber, PVC, Asbestos, Acrylic etc. and found that the combination of PVC and Acrylic in their bulk form (in the form of sheets) is more efficient in triboelectric generation. As observed above, the contact area for rubbing is a crucial parameter and one could have much more output power density by increasing the effective area of contact. However, using materials in their bulk form has limited the electrical output voltage up to ~ 5V. This kind of generation of potential difference can be highly efficient to activate the voltage driven liquid crystal based devices (discussed above) as well as current controlled devices like light emitting diodes too. The use of suitable polymers in their nano-structured form could provide better electrical outputs [10-12]. We, too, are in process to extend our study by involving nano-composites of the triboelectric effective polymers materials and the results will be reported later.

CONCLUSIONS

The triboelectric electricity generation presented in this study relies on the charge pumping effect of the triboelectric potential, and it is a simple, low-cost, scalable engineering approach. We have electrical output of up to a peak voltage of ~ 5 V using the bulk form of polymeric materials (Acrylic and PVC). We found that the triboelectric generation presented could be one of the new classes of triboelectric generators. Further, we observed that sufficient voltage, to activate low power devices, can be generated using triboelectric generation. The fact that devices based on LC materials require the voltage of the order of 2–4 V for the cell gap of few microns, this kind of non-conventional generation of electrical energy can be highly efficient to activate such type of devices. On the other hand, with the suitable integration of this technique, it may be used to generate enough current that could be used to energize devices like LED and electrochromic devices.

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