Electromechanical characterization of a new synthetic rubber membrane for dielectric elastomer transducers

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ABSTRACT

Dielectric Elastomers (DE) are incompressible polymeric solids that experience finite elastic deformations and are electrically non-conductive. Stacking multiple DE films separated by compliant electrodes makes a deformable capacitor transducer, namely a DE Transducer (DET), which can expand in area while shrinking in thickness and vice versa. DETs can be used as solid-state actuators, sensors and generators.

The development of an effective DET requires the accurate knowledge of the constitutive behavior of the employed DE material. In this context, this paper reports the experimental results of the electromechanical characterization of a new synthetic rubber membrane (TheraBand™ Latex Free Resistance Band Yellow (P/N #11726), or TheraBand LFRB-Y in short) to be used as elastic dielectric in DETs. Comparison of the obtained results with those of the best quoted Natural Rubber membrane (OPPO BAND 8003) is also provided that shows the superior performances of TheraBand LFRB-Y both in terms of reduced mechanical hysteresis and of higher dielectric strength stability to ambient wetness conditions.

Keywords: Dielectric Elastomer, Synthetic Rubber, Dielectric Elastomer Generator, Dielectric Strength, Stress-Strain Response.

1. INTRODUCTION

Dielectric Elastomer Transducers (DETs) are deformable capacitors, made by one (or more) incompressible elastic dielectric membrane (namely, the Dielectric Elastomer or DE in short) sandwiched between compliant electrodes. After about 20 years from their first conception[1], a number of potential applications of DETs have emerged as electromechanical sensors, actuators and generators. Examples are[2-4]: actuators for soft robots[5], loudspeakers[6], braille displays[7], strain and pressure sensors[8], tunable lenses[9], fluidic valves[10], and energy harvesters[11,12] to generate electricity from human motion as well as from natural resources (in particular from ocean waves[13-15]). In these application scenarios, the advantages that could be offered by DETs over more conventional technologies are: large converted energy densities, direct-drive and cyclic operation, distributed transduction and good impedance matching capabilities, good energy conversion efficiencies, good shock and corrosion resistance, silent operation and moderate/low cost.

Despite the vast potential, the practical viability of DET technology is nowadays confined to a few niche sectors. Enlarging the spectrum of real-world applications of DETs requires materials with improved electro-mechanical performances; primarily DEs with large dielectric constant, large deformability and high dielectric strength, which are the prerequisite for the development of DETs with high energy densities. Moreover, other aspects such as elastic response, mechanical dissipations (due to viscosity and plasticity), electrical dissipations (due to electrical conductivity) and fatigue life (especially in severe environmental and ageing conditions) cannot be overlooked[16].

To date, the best performing and widely used DE materials are silicone elastomers (for instance Nusil CF19-2186[17-18], Dow Corning HS3[17,18], Dow Corning Sylgard 186[17,18], Wacker Elastosil RT625[19]), acrylic elastomers (in particular the well known VHB 4910 and 4905 by 3M[18,20]) and natural rubber (for instance OPPO BAND 8012[16], OPPO BAND 8003[21] and ZruElast A1040[21]). Silicone elastomers are very soft (with negligible viscosity and plasticity) and usually feature modest dielectric constant and dielectric strength; they are non-reactive, stable, and resistant to extreme environments, which make them particularly suited for the development of sensors[8], optical systems[9] and wearable devices[7]. Acrylic elastomers feature large deformability, good dielectric constant and high dielectric strength, but are very inelastic and sensitive to environmental conditions, which make them adequate for the development of proof-of-

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concept devices mainly. Natural rubber features large deformability (with limited viscosity and plasticity), high dielectric strength and modest dielectric constant; it is rather stiff, which makes it more adequate for the development of energy harvesting devices[21,22] (usage in actuators requires some clever design and complication to compensate for its passive elastic response).

In this context, this paper investigates the primary electro-mechanical properties of a new synthetic rubber membrane (TheraBand™ Latex Free Resistance Band Yellow (P/N #11726) with thickness t_0 = 293μm), hereafter referred to as TheraBand LFRB-Y. In particular, the results of cyclic tensile tests, and of dielectric constant and dielectric strength measurements for the considered material are presented for the first time.

2. DIELECTRIC TESTS

DETs are electrostatic transducers that exploit capacitance variations for the bidirectional conversion of mechanical energy into electricity. A fundamental figure of merit for evaluating the performance of a DET is the quantity

$$\Im = \varepsilon_r E_{BD}^2 , \tag{1}$$

where ε_r and E_{BD} are, respectively, the relative dielectric constant (hereafter called "relative permittivity") and the dielectric strength of the considered material. In fact, both the maximal energy that can be harvested by a DE generator and the maximal thrust that can be produced by a DE actuator are proportional to $\Im$. Despite many materials feature dielectric properties that are constant, certain DEs may exhibit strain-dependent electrical responses.

In the following subsections, the results of the experimental characterization of the dielectric constant and of the dielectric strength of TheraBand LFRB-Y are reported for specimens subjected to different strain levels.

2.1 Dielectric constant measurements

Dielectric constant measurements have been performed with the set-up and procedures described in a previous work[16]. In particular, DE specimens with three different equi-biaxial pre-stretches ($\lambda_{1p} = \lambda_{2p} = \lambda_p$ with λ_p = 1, 2, 3) were first prepared by manually stretching and mounting virgin TheraBand LFRB-Y membranes onto a plastic circular frame (made of polycarbonate) with internal and external radii equaling 120mm and 140mm, respectively. After preparation, each specimen has been subjected to two sets of three capacitance measurements[16]; the first by using unequal rigid brass cylindrical electrodes[16] (with the membrane in contact with the cylinder base) and the second by using painted circular carbon grease electrodes (made with MG-Chemicals 846). In all cases, the active electrode area was A = 452.39mm^2. Measurements have been performed via a LCR bridge (Hameg Instruments LCR meter HM 8118) using a 20Hz and 1.5V$_{\mathrm{RMS}}$ signal with 5V$_{\mathrm{DC}}$ bias. Three measurements have been taken for each pre-stretch and for each electrode case. Upon measurement, the recorded value of capacitance, C, has been used to estimate the dielectric constant of TheraBand LFRB-Y according to the following formula

$$\varepsilon_r = C t_0 \Big/ \left(\lambda_p^2 A \varepsilon_0 \right) , \tag{2}$$

with ε_0 = 8.8e^{-12} F/m. Equation (2) holds under the assumption of DE material incompressibility.

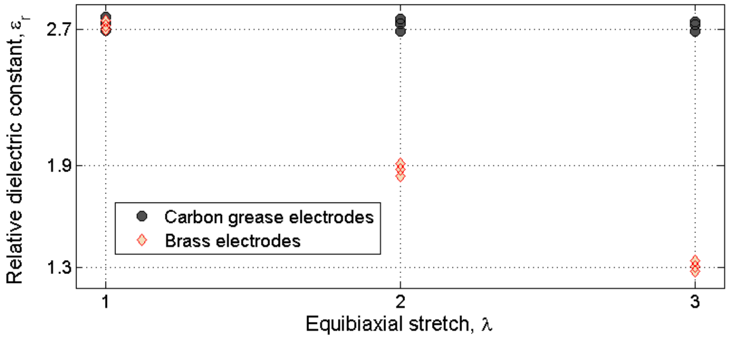

Figure 1: Dielectric permittivity test results of TheraBand™ Latex Free Resistance Band Yellow for different equi-biaxial pre-stretches.

Experimental results are summarized in Figure 1, which reports the measured relative permittivity versus strain for TheraBand LFRB-Y specimens tested with brass electrodes (diamond markers) and with carbon grease electrodes (circle markers). As shown, the estimation of the dielectric constant of the considered DE material is highly affected by the kind of electrodes employed for the measurements. In particular, an almost constant value is obtained with compliant carbon grease electrodes, whereas a strong strain-dependency (with the dielectric constant decreasing as the pre-stretch is increased) is revealed when using rigid brass electrodes.

Although no clear explanation has been found yet, the discrepancy between the two measurements could be attributed to the imperfect contact of brass electrodes (that are rigid) with the tested DE membrane, which is likely to be influenced by the surface texture of the latter (and with the surface texture certainly varying as a function of deformation). As a matter of fact, TheraBand LFRB-Y membrane presents a rather rough lightly ribbed surface texture (see figure 2) which contributes to reduce the effective area of contact with a rigid electrode. As the TheraBand LFRB-Y membrane is deformed, it is likely that the expansion of the surface valleys will be higher than that of the surface peaks, which may further diminish the effective area of contact with the rigid electrode and, thus, lead to an underestimation of the effective value of capacitance (and in turn of the dielectric constant). On the contrary, the liquid-like nature of carbon grease facilitates the intimate contact of the electrode across all peaks and valleys of the surface of the TheraBand LFRB-Y membrane, which is likely to make it more suited to obtain dielectric constant measurements that are less affected by the level of surface roughness of the considered specimen.

For the reasons stated above, the measurements obtained with carbon grease electrodes are considered more reliable. Thus, a strain-independent dielectric constant with value $\varepsilon_r = 2.73$ is attributed to the TheraBand LFRB-Y membrane. This value is very close to that ($\varepsilon_r = 2.8$) found for the OPPO BAND 8003 Natural Rubber membrane[21], which is nowadays deemed the most promising DE material for the development of DET-based energy harvesting devices.

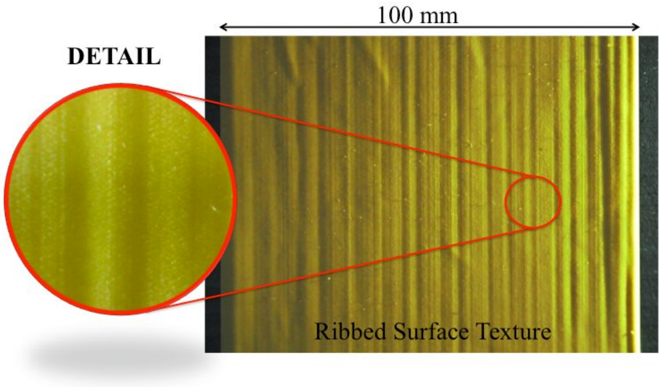

Figure 2: Photograph of the surface of the TheraBand™ Latex Free Resistance Band Yellow; low-angle oblique lighting is employed to emphasize the ribbed surface texture.

2.2 Dielectric strength measurements

Dielectric strength measurements have been performed as described in a previous work[16]. In particular, TheraBand LFRB-Y specimens with three different equi-biaxial pre-stretches ($\lambda_{1p} = \lambda_{2p} = \lambda_p$ with $\lambda_p = 1, 2.041, 3.125$) were first prepared according to the procedure described in Section 2.1. After preparation, each specimen has been subjected to dielectric strength testing using rigid brass cylindrical electrodes[16] (with the membrane in contact with the cylinder base) connected and supplied by a high-voltage DC-DC converter (Ultravolt 40A24-P30-C) with 40kV and 0.75mA maximum voltage and current ratings. The High-Voltage (HV) electrode is 25mm in diameter and 25mm in height. The grounded electrode is 150mm in diameter and 5mm in height. Both HV and grounded electrodes feature edges rounded to give a radius of 0.5mm. As a result, the active electrode area used for dielectric strength testing is $A = 452.39\text{mm}^2$. During testing, the two electrodes are arranged coaxially within 5mm. To insure safety, the HV electrode is fully embedded in a plastic cylindrical receptacle (constituted by two parts made in Delrin®) that closes onto the DE membrane specimen[16]. This protects the HV electrode from the user touch and interrupts the air path to the ground electrode. Measurements have been performed in “short-time” (or rapid-rise) test mode. Specifically, the voltage is raised from zero at a uniform rate (chosen among the values 500V/s, 1000V/s and 2000V/s) until break-down occurs; with the specific rate of rise being selected for each specimen so as to cause the rupture most commonly to happen between 10s and 20s. Logging of the data has been accomplished by acquiring the voltage difference across the brass electrodes using a USB-based oscilloscope (PicoScope 2202) equipped with a custom-made 4000:1 HV probe. A minimum of nine measurements have been taken for each pre-stretch case. Upon measurement, the recorded value of potential difference, V_{BD}, has been used to estimate the dielectric strength of TheraBand LFRB-Y according to the following formula

$$E_{BD} = V_{BD}\lambda_p^2 / t_0, \tag{3}$$

which holds under the assumption of material incompressibility.

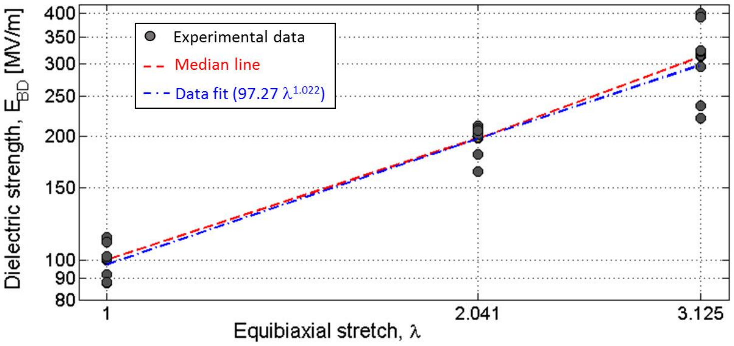

Figure 3: Dielectric strength test results of TheraBand™ Latex Free Resistance Band Yellow for different equi-biaxial pre-stretches.

Experimental results are summarized in Figure 3, which reports the measured dielectric strength versus strain for all the tested TheraBand LFRB-Y specimens. In figure, circle markers identify the obtained experimental data, the red dotted line represents the line joining the median values obtained for each pre-stretch case, whereas the blue dash-dotted line is the curve fitting of all data with the function $E_{BD} = a \cdot \lambda^R$ (optimal fit for a = 97.27MV/m and R = 1.022) that is frequently used in the literature[12,21]. As shown, the dielectric strength of TheraBand LFRB-Y increases significantly with strain. Despite the significant variability, the recorded values are all very good, with minimum dielectric strength higher than 88MV/m for λ_p = 1, 160MV/m for λ_p = 2.041 and 220MV/m for λ_p = 3.125 (and with much larger median values: 100MV/m for λ_p = 1, 198MV/m for λ_p = 2.041 and 313MV/m for λ_p = 3.125). Similar dielectric strength results have also been obtained by using carbon grease electrodes.

As compared to other DE materials, the dielectric strength values recorded for TheraBand LFRB-Y are very similar to those found for the OPPO BAND 8003 Natural Rubber membrane[21] (for which $E_{BD} = 97\lambda^{0.99}$ MV/m), which is nowadays deemed the most promising DE material for the development of DET-based energy harvesting devices.

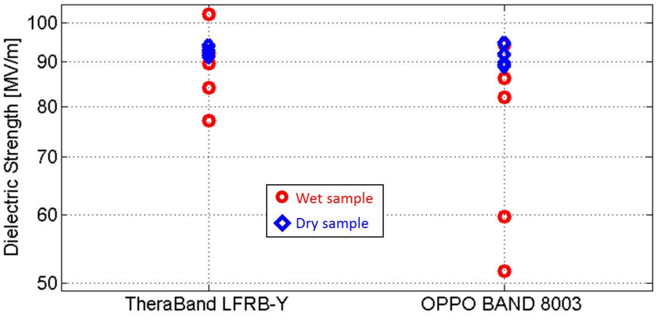

Figure 4: Comparison of dielectric strength test results for wet (in circle markers) and dry (in diamond markers) samples of un-stretched TheraBand™ Latex Free Resistance Band Yellow (on the left) and OPPO BAND 8003 (on the right) membranes.

To preliminary assess the degradation of membrane properties in wet environments (and the eventual recovery), additional virgin specimens of TheraBand LFRB-Y were immersed into water for two days and then subjected to dielectric strength testing in either wet (samples dried with a towel for a few minutes and left for 1 hour at room temperature) and dried (samples dried in an oven at 40°C for 2 hours) conditions. For the sake of comparison, the same tests have also been performed for the OPPO BAND 8003 Natural Rubber membrane[21]. Results are reported in Figure 4, which highlights that immersion into water causes a significant reduction in dielectric strength for the OPPO BAND 8003 and almost no variation in the response of TheraBand LFRB-Y. This is most probably due to the higher water adsorption/permeability of the Natural Rubber membrane. Nonetheless, the same results also show that the observed reduction in dielectric strength with water immersion can be recovered almost completely upon extensive drying of the membrane.

3. MECHANICAL TESTS

For the characterization of the mechanical response, a pure-shear specimen of TheraBand LFRB-Y has been subjected to cyclic tensile tests with the set-up and procedures described in a previous work[16]. The considered pure-shear specimen was 10mm long in the longitudinal direction, 200mm long in the transversal direction and 293μm in thickness. No pre-stretch has been applied in the transversal direction. Three cyclic tensile tests have been performed on the same specimen, each having a different value for the maximum deformation but performed at the same deformation rate of $0.3s^{-1}$. To remove any stress-softening effect, each tests consisted in ten identical loading-unloading cycles, out of which only the last one has been retained and considered as the stabilized stress-strain response of the specimen.

Test results are provided in Figure 5, which reports the stabilized stress-strain response of TheraBand LFRB-Y for the following three different maximal stretches: $\lambda_1 = 4.4$, $\lambda_1 = 5.1$ and $\lambda_1 = 5.6$. As shown, TheraBand LFRB-Y behaves very well in a wide range of deformations, featuring very little hysteresis (specifically, very little viscous and plastic effects).

For the sake of comparison, similar pure-shear tests have also been performed on an OPPO BAND 8003 Natural Rubber membrane specimen with 220μm thickness. Results are reported in Figure 6 for three different maximal stretches ($\lambda_1 = 4.4$, $\lambda_1 = 5.4$ and $\lambda_1 = 5.9$), which highlights that this latter material has a more hysteretic response than that of TheraBand LFRB-Y.

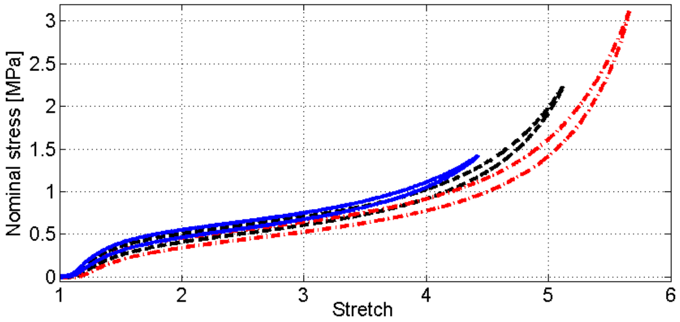

Figure 5: Stabilized stress-strain response of a pure-shear TheraBand LFRB-Y specimen with transversal pre-stretch $\lambda_{2p} = 1$.

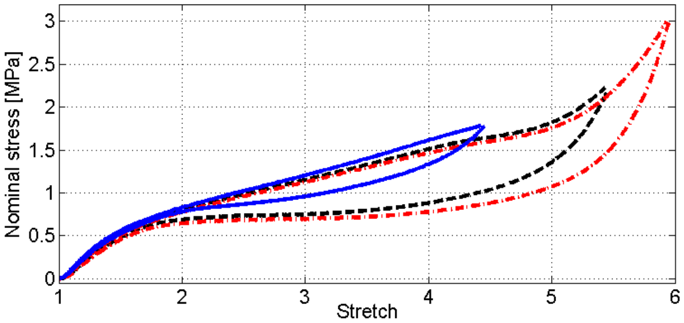

Figure 6: Stabilized stress-strain response of a pure-shear OPPO BAND 8003 specimen with transversal pre-stretch $\lambda_{2p} = 1$.

4. CONCLUSIONS

This paper presented the first results on the electromechanical characterization of a synthetic rubber band (TheraBand™ Latex Free Resistance Band Yellow (P/N #11726), or TheraBand LFRB-Y in short) to be used as a new dielectric elastomer material for the development of solid-state electromechanical transducers.

Experimental results from cyclic tensile tests, dielectric constant and dielectric strength measurements highlight that TheraBand LFRB-Y exhibits electromechanical properties that are comparable or better than those of the best performing natural rubber membrane that is acknowledge in the literature. Moreover, the proposed material showed two particular interesting features that are (1) a distinctive insensitive electrical response to wetness and (2) an extremely reduced hysteresis in its mechanical response. These two qualities make the TheraBand LFRB-Y an extremely promising material for implementing DETs to be employed as generators in marine applications such as wave energy harvesting.

In the future, experimental characterization of dissipative effects (including mechanical viscosity and plasticity and electrical bulk conductivity) and fatigue life will be performed to assess the adequacy of TheraBand LFRB-Y for the development of high-performance dielectric elastomer transducers for real-world applications.

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REFERENCES

[1] Pelrine, R.E., Kornbluh, R.D., Joseph, J.P., “Electrostriction of polymer dielectrics with compliant electrodes as a means of actuation,” Sensors and Actuators A: Physical, 64(1), 77-85 (1998)

[2] Kornbluh, R. D., Pelrine, R., Pei, Q., Heydt, R., Stanford, S., Oh, S., Eckerle, J., “Electroelastomers: applications of dielectric elastomer transducers for actuation, generation, and smart structures,” in Proc. SPIE Vol. 4698, 254-270 (2002).

[3] Carpi, F., De Rossi, D., Kornbluh, R., [Dielectric elastomers as electromechanical transducers: Fundamentals, materials, devices, models and applications of an emerging electroactive polymer technology], Elsevier Science (2008).

[4] OHalloran, A., OMalley, F., McHugh, P., “A review on dielectric elastomer actuators, technology, applications, and challenges,” Journal of Applied Physics, 104(7), 071101-071101 (2008).

[5] Choi, H. R., Ryew, S., Jung, K. M., Kim, H. M., Jeon, J. W., Nam, J. D., Tanie, K., “Soft actuator for robotic applications based on dielectric elastomer: quasi-static analysis,” in IEEE International Conference on Robotics and Automation, Vol. 3, 212-3217 (2002).

[6] Heydt, R., Kornbluh, R., Eckerle, J., Pelrine, R., “Sound radiation properties of dielectric elastomer electroactive polymer loudspeakers,” in Proc. SPIE Vol. 6168, 61681M-61681M (2006).

[7] Matysek, M., Lotz, P., Schlaak, H. F., “Tactile display with dielectric multilayer elastomer actuators,” in Proc. SPIE Vol. 7287, 72871D (2009).

[8] O'Brien, B., Thode, J., Anderson, I., Calius, E., Haemmerle, E., Xie, S., “Integrated extension sensor based on resistance and voltage measurement for a dielectric elastomer,” in Proc. SPIE Vol. 6524, 652415-652415 (2007).

[9] Carpi, F., Frediani, G., Turco, S., De Rossi, D., “Bioinspired Tunable Lens with Muscle-Like Electroactive Elastomers,” Advanced Functional Materials, 21(21), 4152-4158 (2011).

[10] Giousouf, M., Kovacs, G., “Dielectric elastomer actuators used for pneumatic valve technology,” Smart Materials and Structures, 22(10), 104010 (2013).

[11] Pelrine, R., Kornbluh, R., Eckerle, J., Jeuck, P., Oh, S., Pei, Q., Stanford, S., “Dielectric elastomers: generator mode fundamentals and applications,” in Proc. SPIE Vol.Vol. 4329, 148-156 (2001).

[12] Koh, S.J.A., Keplinger, C., Li, T., Bauer, S., Suo, Z., “Dielectric elastomer generators: How much energy can be converted?,” Mechatronics, IEEE/ASME Transactions on 16(1), 33–41 (2011).

[13] Chiba, S., Waki, M., Kornbluh, R., Pelrine, R., “Innovative power generators for energy harvesting using electroactive polymer artificial muscles,” in Proc. SPIE 6927(1), 692715–692719 (2008).

[14] Jean, P., Wattez, A., Ardoise, G., Melis, C., Van Kessel, R., Fourmon, A., Barrabino, E., Heemskerk, J., Queau, J.P., “Standing wave tube electro active polymer wave energy converter,” in Proc. of SPIE Vol 8340, 83400C–1 (2012).

[15] Vertechy, R., Fontana, M., Rosati Papini, G.P., Forehand, D., “In-tank tests of a dielectric elastomer generator for wave energy harvesting,” in Proc. SPIE 9056, 90561G-1-11 (2014).

[16] Vertechy, R., Fontana, M., Stiubianu, G., Cazacu, M., “Open-access dielectric elastomer material database,” in Proc. SPIE 9056 , 90561R-1-13 (2014).

[17] Pelrine, R., Kornbluh, R., Joseph, J., Heydt, R., Pei, Q., Chiba, S., “High-field deformation of elastomeric dielectrics for actuators,” Materials Science and Engineering: C, 11(2), 89-100 (2000).

[18] Brochu, P., Pei, Q., "Advances in Dielectric Elastomers for Actuators and Artificial Muscles, “Macromolecular Rapid Communications, 31(1), 10-36 (2010).

[19] Vudayagiri, S., Zakaria, S., Yu, L.,Hassouneh, S.S., Benslimane, M., Skov, A.L., “High breakdown-strength composites from liquid silicone rubbers,” Smart Materials and Structures, 23(10), 105017 (2014).

[20] Pelrine, R., Kornbluh, R., Pei, Q., Joseph, J., "High-Speed Electrically Actuated Elastomers with Strain Greater Than 100%,” Science, 287(5454), 836-839 (2000).

[21] Kaltseis, R., Keplinger, C., Koh, A.S.J., Baumgartner, R., Goh, Y.F., Ng, W.H., Kogler, A., Trols, A., Foo, C.C., Suo, Z., Bauer, S., “Natural rubber for sustainable high-power electrical energy generation,” RSC Advances, 4(53), 27905-27913 (2014).

[22] Moretti, M., Fontana, M., Vertechy, R., “Parallelogram-shaped dielectric elastomer generators: analytical model and experimental validation,” Journal of Intelligent Material Systems and Structures, doi: 10.1177/1045389X14563861, published online before print December 19 (2014).