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Carbon Black based capacitive Fractional Order Element towards a new electronic device

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ABSTRACT

In this paper, Fractional Order Elements (FOEs), fabricated by using a carbon black nano structured dielectrics, are presented. FOEs have been realized by varying different fabrication parameters such as the percentage of carbon black, the curing temperature, and the solvent type.

Results on the experimental frequency characterization of one FOE device are given. The FOE has been, then, used for demonstrating the possibility of realizing a fractional order *RC* filter.

The frequency analysis of the *RC* filter shows the coherence of the fractional order between the FOE and corresponding *RC* circuit.

1. Introduction

Fractional calculus is a quite general approach that has been already proposed in a growing numbers of fields, due to its capability of modeling and controlling systems characterized by long term properties [1].

Typical applications can be found in automatic control area. In [2], fractional order PID controllers have been introduced. Their stability region have been investigated in [3]. The corresponding tuning procedure has been introduced in [4]. Applications, both in analog [5] and digital [6,7] controller implementation, have been proposed.

Applications to system modeling can be found in the supercapacitor area [8], as well as in medical applications [9,10]. More specifically, in [9], the human respiratory system is emulated, using approximated fractional-order capacitors and inductors. In [10] the identification of a model for respiratory tree, by using an equivalent electrical model, is proposed.

The relationship between chaos and fractional order systems has been investigated in [11], while their Lyapunov exponents characterization is introduced in [12].

Applications, related to electronic devices can be found in [13], where the numerical analysis of the fractional harmonic oscillator has been proposed. The Fractional Order Impedance (FOI) characterization has been studied in [14–16].

Modeling of non integer order electronic devices is needed for the devices proposed in this paper. Resistors (R), inductors (L) and the capacitors (C) are electric passive circuit elements, whose impedance is given by:

$$Z(s) = Ks^{-\alpha} \tag{1}$$

where K is a gain, s represents the Laplace variable and $\alpha \in \{-1,0,1\}$, for capacitor, resistor and inductance, respectively.

The impedance is described in the frequency domain by substituting $j\omega$ for s, where j is the imaginary unit and w is the angular frequency.

The impedance then becomes:

$$Z(jw) = K(jw)^{-\alpha} \tag{2}$$

The magnitude and phase of this impedance are $|Z| = K/w^{\alpha}$ and $Arg(Z) = -\alpha\pi/2$, respectively. For $\alpha \in \{-1,0,1\}$, the phase is $\pi/2$ (i.e., inductor), 0 (i.e., resistor), and $-\pi/2$ (i.e., capacitor), respectively.

Actually, the value of α is not necessary an integer number. It can rather assume any value in $\mathbb{C}$. In such a case, the systems are modeled using the fractional order approach, see [17,18].

According to (2) a fractional element exhibits a constant phase behavior and is often referred as a Constant Phase Element (CPE). The availability of CPEs will play a fundamental role in the possibility of realizing non integer order electronic circuits. CPE realization and applications can be found respectively [19–22].

Realization of Fractional Order Element (FOE), have been proposed in [23,24] where electrolytic process and Ionic Polymeric Metal Composite, respectively, are investigated in the perspective of the

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realization of fractional order capacitors. Nanocomposite based fractional capacitor have been proposed in [25] and their packaging study is given in [26].

The focus of this paper is on the possibility of exploiting nanostructured materials, in particular Carbon Black (*CB*) based composites, for realizing non integer order devices. More specifically, CB composites are exploited for realizing the dielectric of capacitors that can be modeled as *FOEs*. By using such components, a new class of filters is proposed, with frequency characteristics that can not be easily obtained by using traditional components.

The realization of analog fractional order systems, in the form of fractional order filters, represents the counterpart of their digital implementation [7]. At present, fractional order transfer functions are essentially digitally implemented. The fractional order and the corner frequency approximations bring to the implementation of high order digital filters. In the paper the possibility of using the proposed FOEs for realizing RC filter is implemented in hardware. This allows for directly using an analog device, without any approximation.

2. Carbon Black as dielectric for new FOE electronic devices

It is widely known in the literature that, by adding a conductive filler to an insulating matrix (generally a polymeric matrix), both the electrical and mechanical properties of the composite can change dramatically. Such a phenomenon has been widely exploited for realizing polymer conducting composites, with application, e.g., such as thermistors, deformation sensors [27], pressure sensors [28], tactile sensors, and gas sensors [29]. Here, the possibility of using CB, as the filler of a polymeric matrix, for realizing nano composites with dielectrics properties is investigated.

$Sylgard_{184}$ has been used for realizing the polymeric matrix of the capacitor dielectric. It was purchased from *DowCorning* as a two part liquid elastomer kit. Part A (consisting in the vinyl-terminated PDMS prepolymer), and Part B (the crosslinking curing agent, consisting in a mixture of methylhydrosiloxane copolymer chains with a Pt catalyst and an inhibitor).

CB (acetylene, 100% compressed, 99.9%, specific area 75 m^2/g, bulk density 170–230 g/L, average particle size 0.042 μm) was purchased from *AlfaAesar* and used as received. The described CB based composite material is the dielectric of the capacitances investigated in the following of the paper. The resulting structure of the CB-Fractional Order Element (CB-FOE) is given in Fig. 1.

The CB-FOE samples have been prepared by mixing the *PDMS* and the crosslinking agent in a weight ratio of 1:10 in a Teflon crucible. The mixture was mixed for 10 min. CB has been added for achieving the desired concentration. The mixture was stirred for further 10 min for enhancing the dispersion of the CB.

Curing at different temperatures were carried out, taking into account both the manufacturer recommended curing time and the heat propagation through the mold. This results in a stabilization time, required for the temperature of the curing *PDMS* approaching the desired curing temperature. The mixture was used for realizing the capacitors dielectric by pouring the viscous mixture into the device. The mixture was allowed to crosslink at room temperature, or in an oven preheated to the desired temperature, for 48 h. More specifically, the obtained dielectrics have been used to realize cylindrical capacitors, whose geometry is shown in Fig. 2. Capacitances considered in the following had copper-based shell with hight $h = 8$ cm, internal diameter $a = 0.6$ cm and external diameter $b = 1.2$ cm.

The curing time was 53 min at 100 °C,38 min at 125 °C, and 28 min at 150 °C.

The CB percentage, the curing temperature and the solvent type, have been fixed as reported in Table 1.

Experiments reported in the following will refer only to the capacitors $C-100$,$C-150$ and $C-200$, all realized with a CB percentage of 8%. This choice comes from the idea of characterizing the capacitors with respect to the curing temperature parameter.

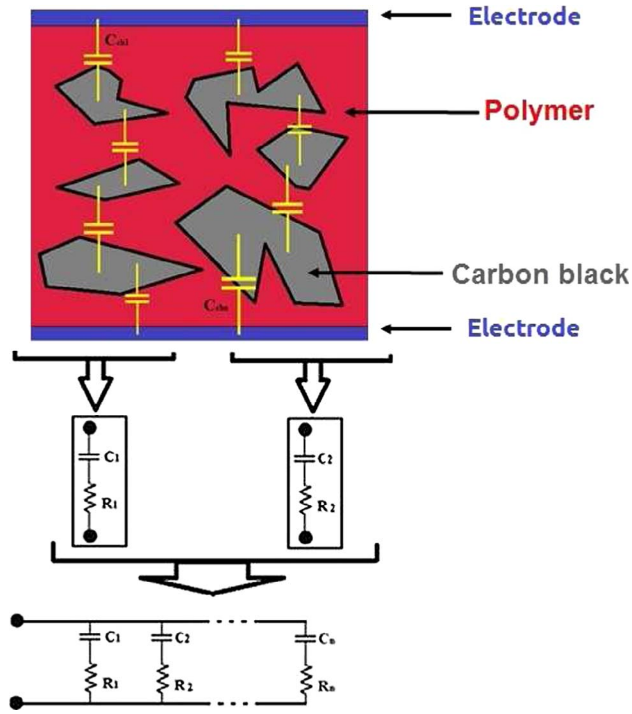

Fig. 1. A scheme of the CB-FOE structure and corresponding electrical approximation.

As a first step, the frequency behavior of the capacitive devices has been investigated. The experimental surveys were performed by using a network analyzer Agilent Technologies E5071B. Moreover, the devices were connected to the measuring instrument, by using adequate connectors, in such a way to avoid any high-frequency parasitic effect. A picture of a FOE device under test, along with the used connector is shown in Fig. 3.

As an example, the results of the frequency analysis of the FOE C-125 is shown in Fig. 4. As it can be noticed, in the frequency range 10^5–10^9 Hz, the phase assumes approximatively a constant value equal to −75°. Such a phase value corresponds to $\alpha = 0.85$. The slope of the magnitude diagram is equal to 17.14 dB/dec, which is in good agreement with expected value, i.e. $\alpha*20$ dB = 0.85*20 dB = 17 dB/dec.

3. RC filters by CB-FOE

The CB-FOE element, described so far can be valuable resource for the hardware implementation of non integer order filters. In the following, experimental results obtained by the investigation of non integer order low-pass filters. fabricated by using the CB-FOE capacitors, are reported.

When a low pass filter is considered, the transfer function assumes the following form:

$$Z(s) = \frac{K}{(1+\tau s)^{\alpha}} \tag{3}$$

where τ is the pole of the system and, as reported in Section 1, $\alpha \in \mathbb{C}$.

The fractional nature of (3) reflects in its Bode diagram. More specifically, both the asymptotic slope of the magnitude and the phase, are multiplied by α. If $\omega \to \infty$,$|Z|$ becomes $-20\alpha\log_{10}(\omega\tau)$. On a semi-logarithmic plane, a line with slope $-20\alpha\,\frac{\mathrm{dB}}{\mathrm{dec}}$ (instead of −20 dB/dec as for first order system), will be observed. The expression of $Arg(Z)$ shows that α modulates the scale of the phase law [17]. In fact, it can be easily seen that, for $\omega \to \infty$, the phase angle approaches $-\alpha\pi/2$, instead of $-\pi/2$, as it occurs for a first order low-pass filter.