Fabrication of a Fractional Order Capacitor With Desired Specifications: A Study on Process Identification and Characterization

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***Abstract*—This paper reports the fabrication of a fractional order element (FOE) with predefined specifications. The FOE is a circuit element similar to resistance, capacitance, and inductance generally used in electrical network. The specifications of integer order elements, i.e., inductance, resistance, and capacitance, are defined by the magnitude only as their exponents are of fixed value, namely, −1, 0, and +1, respectively. The specialty of FOE is that both its magnitude and exponent value have to be defined, where the value of the exponent dictates the behavior. This paper elaborately discusses the methodology of realizing a fractional order capacitor named here as FOE (or, in general, FOE). It has been found that a FOE can be realized by dipping a capacitive-type probe, coated with a porous film of polymer of particular thickness, into a polarizable medium. The thickness, uniformity, and stability of the porous film, on the electrode, are responsible for different exponent values.**

***Index Terms*—Constant phase angle (CPA), fractional exponent, fractional order capacitor, poly(methyl methacrylate) (PMMA), porous film.**

I. Introduction

INDUCTANCE, resistance, and capacitance are well-known passive circuit elements. The impedance of these elements [1] can be represented by the general equation

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

where Q is a coefficient, α (a real number) is the exponent of the element, and s denotes the Laplace operator. For the integer values of α $(-1, 0, +1)$, the element is an inductance, resistance, or capacitance. However, if the noninteger value of α exists, then the element can be called as a fractional order element (FOE), an additional circuit element in the electrical domain. The coefficient Q and the exponent α for FOE then can be obtained by expressing (1) as $Z_{\mathrm{FOE}}(j\omega) = Q(j\omega)^{-\alpha}$, where ω is the angular frequency in radians per second, which results in

$$\angle Z_{\mathrm{FOE}} = -\frac{\alpha \times \pi}{2}, \text{ or } \alpha = -\frac{2 \times \angle z_{\mathrm{FOE}}}{\pi}; \text{ and}$$
$$Q = |Z|\omega^{\alpha}. \tag{2}$$

From "(2)," it is evident that the fractional exponent "α" dictates the behavior of FOE and is dependent on the phase angle $\angle Z_{\mathrm{FOE}}$ of the element but independent of ω. On the other hand, the coefficient Q depends on the magnitude $(|Z|)$ and on the value of α as well as on the ω. Hence, it can be said that a FOE can be realized if it shows a constant phase angle (CPA), $\angle Z_{\mathrm{FOE}}$, over all frequencies.

There are few reports available in the literature on the practical realization of FOE which can be used in a circuit, although many researchers have used the output of mathematical simulation in place of physical FOE [2]–[7]. The first attempt to realize an analog FOE was perhaps by constructing infinite ladder network [8], but that is not very suitable to generate FOE of any value of α. Moreover, the circuits become bulky. It has been reported that FOE can be realized by developing fractal structures on silicon [9], but the exponent value lies in the range of 0.46–0.5 as similar to ladder network. Bohannan of Wavelength Electronics reported the realization of fractional order circuit element by developing lithium ions on the rough surface of metal electrodes [10]. However, by this method, it is not easy to reproduce a FOE with desired specifications. Recently, the development of fractional order capacitors based on electrolytic processes has been reported [11], but again, the dimension of the electrodes is a big concern and its reproduction is difficult. The other approach is to realize a fractional order capacitor named here as FOE by dipping a capacitive-type polymer-coated probe in polarizable medium [12]–[14], which can be easily fabricated and is a suitable candidate to be used in electrical circuits. It has been mentioned in [12]–[14] that the phase angle (or, in other words, fractional exponent α) of the FOE may be formulated as

$$\angle Z_{\mathrm{FOE}} = f(t, A, \sigma) \tag{3}$$

where t is the coating thickness of a porous film on the electrodes, A is its dipping area within the polarizable medium,

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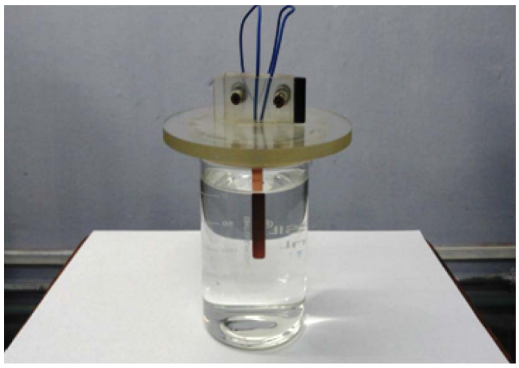

Fig. 1. Photograph of FOE in laboratory.

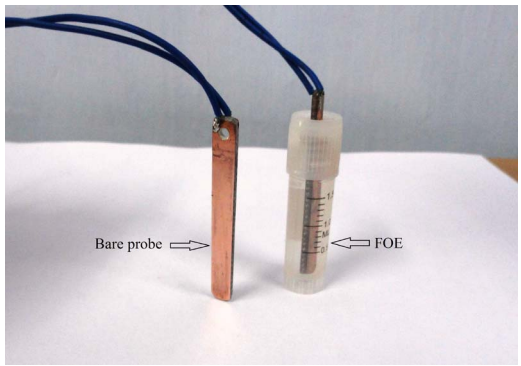

Fig. 2. Photograph of probe used and FOE in a package.

and σ is the ionic property of the polarizable medium. For the fabrication of FOE as a circuit element, it is an important task to establish a relationship between the phase angle and the three parameters (t, A, and σ) as stated in (3). It has been observed in [14]–[16], and a preliminary study indicates that the phase angle follows an almost linear relationship with the two factors A and σ. Hence, these two may be used for fine tuning to obtain a specific value of α. However, the relation with the third parameter t will be obtained if different sets of identical FOEs with different values of α can be realized, and the successful realization of FOE lies mainly on coating the electrodes with a porous film having the required thickness and on its stability and uniformity. Therefore, the aim of this study is to develop a methodology to fabricate identical FOEs with predefined specifications.

In [12]–[14], the probe has been developed by coating a thin microporous film of poly(methyl methacrylate) (PMMA) of thickness (t) on a copper-clad printed circuit board of suitable dimension using dip coating technique. However, this method is not suitable to reproduce identical probe of the same coating thickness, and the main challenge remains in designing the fabrication process so that the FOE can be reproduced repeatedly with desired specifications. A method has been developed by finding the nature of the change of Q and α with the change of t (keeping the values of A and σ constant). This paper has been organized as follows. In Section II, the fabrication methodology is presented elaborately, including different aspects which may be responsible to obtain identical FOEs. The characterization of the fabricated FOEs is also presented for the performance study. Next, in Section III, identical FOEs are fabricated, and statistical analysis is provided to judge the success rate on the basis of its performance. Section IV discusses the results and concludes this paper.

II. Methodology

It has been mentioned earlier that a FOE can be realized if the probe (shown in Fig. 2) with porous film on its electrodes is dipped inside a polarizable medium (shown in Fig. 1 in laboratory scale and in Fig. 2 as a packaged form). It has also been mentioned that the property of the porous film dictates the specifications of the FOE, and the other parameters, as given in "(3)," can be used for further tuning. The fabrication of the probe takes care of the size, the properties of the film used for coating, and the technique of coating in detail. Next, characterization has been carried out to study the success of realization of different FOEs with different Q and α and also to identify the bandwidth of the elements.

A. Fabrication of FOE

For the development of a porous film of PMMA on the electrode surface, the steps used are as follows.

1) A strip has been cut from a copper-clad printed circuit board of dimension 50 mm × 6 mm × 1.50 mm. This size has been used to make it a stick type and encapsulated in a container as shown in Fig. 2. However, any desired size can be used.
2) The strips were then properly cleaned, and the edges have been smoothened to get uniform and stable coating on all the surfaces. These strips are called as electrodes.
3) PMMA–chloroform solution of 5% concentration has been prepared. A point to be mentioned is that care should be taken regarding the property and concentration of PMMA–chloroform solution as it plays a vital role on the coating. A detail study, stated in the Appendix, has been done on the property by studying the density, resistivity, and molecular weight of PMMA and the viscosity of the prepared solution. Moreover, it has been observed that the concentration of 5% PMMA in chloroform is optimum because more than this makes the solution thicker and not slide over the metal surface of the electrode during spin. Hence, it will not produce uniform coating and porous structure on the metal surface.
4) For uniform coating, on all the surfaces, the electrodes were first dipped into PMMA–chloroform solution, and then, instead of drying it in air as done in [14], spin coating technique has been used. The speed of rotation and time or number of rotations of the rotor of the spin coating machine are the other two important factors for achieving the desired, uniform, and stable thickness of coating. From preliminary study, it has been observed that, to get a 6 μm coating thickness, the speed of the rotor of the spin coating machine has to be set at 600 r/min with the time of rotation at 120 s. It has also been observed that this is the optimum time of rotation and the time lesser or greater than 120 s fails to produce uniformity and stability of coating. The spin coating machine used was

TABLE I
DISTRIBUTION OF COATING THICKNESS OBTAINED FROM THREE BATCHES OF FABRICATION WITH DIFFERENT ROTOR SPEEDS

Batch No.	Number of probes fabricated	Rotation of Rotor		Distribution of coating thickness	
		Speed in rpm	Time in s	Coating thickness in μm	Number of probes
1	10	600	120	4	1
				5	1
				6	**7**
				7	1
2	10	800	120	3	1
				3.5	1
				4	**8**
3	10	1000	120	2	1
				2.5	2
				3	**7**

model-SCU-2007, where a special indigenous sample holder has been designed and developed for particular use. With this knowledge, ten electrodes are coated adopting the same methodology, and out of them, seven are obtained with a 6 μm coating thickness. These electrodes coated with PMMA were called as probes. Then, to get other coating thicknesses, another ten probes have been fabricated with the rotor speed set at 800 r/min and further ten probes with 1000 r/min, and the time of rotation was set at 120 s. The distribution of coating thickness thus obtained is given in Table I. The thicknesses of all the probes are measured by a high-resolution micrometer (Model: Mitutoyo S112M) before and after coating.

From Table I, it may be said that, if the time of rotation of the rotor is 120 s and its revolutions per minute are kept at a particular value with 5% PMMA in chloroform as dipping solution, then 70% of the probes will attain a particular thickness. However, few probes have thicknesses other than the particular value. This may be due to the limitation of this particular machine where there is a slight variation of rotor speed within $\pm$20 r/min.

Realization of FOE with these probes will only be ascertained after characterizing them by observing the change of impedance with frequency. Ideally, FOE should have a CPA for all frequencies, but practically, it will suffice to say that a FOE has been realized for a particular frequency range if it shows a CPA at least for that range. Of all the probes fabricated, three probes from each with coating thicknesses of 5 μm (named as FOE1_5μm to FOE3_5μm), 6 μm (named as FOE1_6μm to FOE3_6μm), and 7 μm (named as FOE1_7μm to FOE3_7μm) have been chosen for characterization.

B. Characterization of FOE

Characterization of the probes has been carried out to check the constant value of the phase. The property of the polarizing medium and the height of the probe dipped inside the medium are kept fixed to find the change of behavior of the impedance with thicknesses. The polarizing medium is a buffer pH 4.0 solution, and the dip-in length (d) is chosen as 2 cm as it provides a CPA of -11° approximately. To identify the

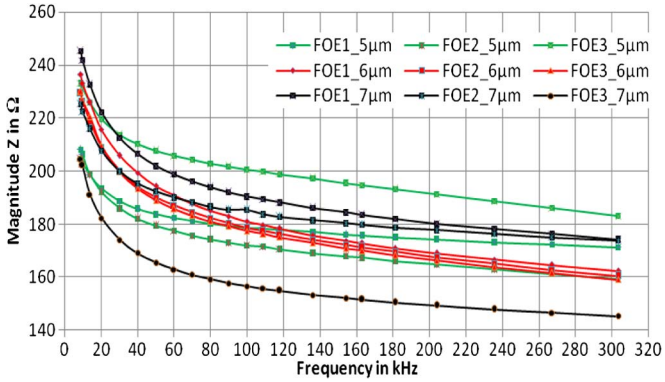

Fig. 3. Change of magnitude with change of thickness in the frequency range of 9–300 kHz.

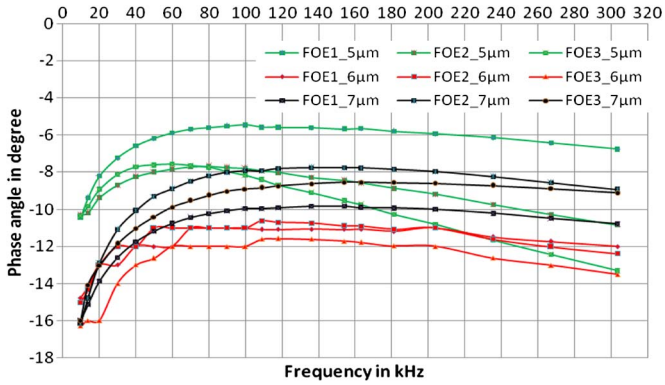

Fig. 4. Change of phase angle with change of thickness in the frequency range of 9–300 kHz.

bandwidth of FOE, the magnitude (Z) and phase angle (θ) have been recorded by an LCR meter (Agilent impedance analyzer model no. 4294A in Z, θ mode) with a sinusoidal signal of 1 V peak to peak in the frequency ranges of 1–10 kHz, 10–100 kHz, 50–500 kHz, 100 kHz–1 MHz, and 1–4 MHz. The entire experimentation was performed in a controlled room temperature of 20 °C so as not to affect the change by any other factor, and each reading was repeated five times (runs) in order to check the repeatability. It has been observed that they exhibit CPA within a particular range of frequency. Figs. 3 and 4 show the magnitude and phase angle behavior of the fabricated FOEs.

The effect of the change of thickness is observed by plotting the impedance (both magnitude and phase angle) of the element in the frequency range of 9–300 kHz, although the reading has been recorded for 1 kHz to 4 MHz. The nature of the change of magnitude in the frequency range, as observed in Fig. 3, is exponentially decreasing as expected from "(2)." It is observed from Fig. 4 that the phase angle is almost constant within $\pm 2^\circ$ in the frequency range of 20–200 kHz and it has a lesser deviation in smaller frequency range. The CPA of all three FOEs with a 7 μm coating thickness is within -10° to -8°, while that of the FOEs with a 6 μm coating thickness is within -12° to -11°, and of all three FOEs with a 5 μm coating thickness, one shows CPA behavior whose value is -6° while the other two show the phase angle of -8°. However, both magnitudes and phases are different for different coating thicknesses even if the area and ionic concentration of the medium are kept the same. The

TABLE II
VALUES OF α AND Q OBTAINED FROM AVERAGE VALUE OF MAGNITUDE AND PHASE ANGLE WHEN PROBE IS DIPPED IN pH 4.0 SOLUTION

d in cm	t µm	Probe no.	At 100kHz value of			
			θ in deg	Z in Ω	α	Q
2	5	FOE1_5 µm	-6	178.5	0.06	401.5
		FOE2_5 µm	-8	172.1	0.09	547.6
		FOE3_5 µm	-8	200.5	0.09	674.7
	6	FOE1_6 µm	-11	181.1	0.12	925.7
		FOE2_6 µm	-11	178.7	0.12	913.9
		FOE3_6 µm	-12	177.4	0.13	1052
	7	FOE1_7 µm	-10	190.4	0.11	834.6
		FOE2_7 µm	-8	185.4	0.09	600.2
		FOE3_7 µm	-9	156.5	0.10	586.5

TABLE III
DISTRIBUTION OF COATING THICKNESS

Number of probes fabricated	Rotation of Rotor		Distribution of coating thickness	
	Speed in rpm	Time in s	Coating thickness in µm	Number of probes
35 (in three batches)	600	120	4	4
			5	5
			6	22
			7	4

values of α and Q have been calculated from the corresponding value of the magnitude and phase angle of the elements at a 100-kHz frequency and are provided in Table II.

From Table II, it may be inferred that an identical FOE with α with a value of approximately 0.1 can be developed if a probe with a coating thickness of 6 μm and a dip length of 2 cm is dipped into pH 4.0 solution.

III. REALIZATION OF IDENTICAL FOE

From the aforementioned discussion, it is evident that successful fabrication of identical FOEs with this method lies in the generation of probes having coating of PMMA of the same thickness. To find the repetitiveness, it was aimed to produce a probe with a coating thickness of 6 μm as this exhibited the most stable result of $\alpha = 0.1$ (approximately).

A. Fabrication of Identical FOE

Three batches of probes have been fabricated with rotor speed of 600 r/min and time of rotation of 120 s, and the concentration of the PMMA–chloroform solution is kept 5% with the methodology as mentioned in Section II.

The distribution of the coating thickness obtained is tabulated in Table III from which it can be claimed that, with this methodology, it is possible to fabricate probes of the same thicknesses repetitively.

Again, it has been observed that FOE can be realized if and only if there is formation of porous structure on a metallic surface [9]. The image of the coating film for a 6 μm probe obtained by a field emission scanning electron microscope (SEM) (FESEM model no. JEOL - JSM - 6700F) as given in Fig. 5 shows the porosity of the coating film.

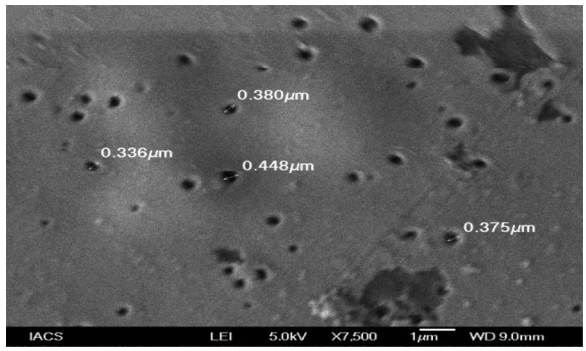

Fig. 5. SEM image of the surface of the probe with 6-μm coating thickness.

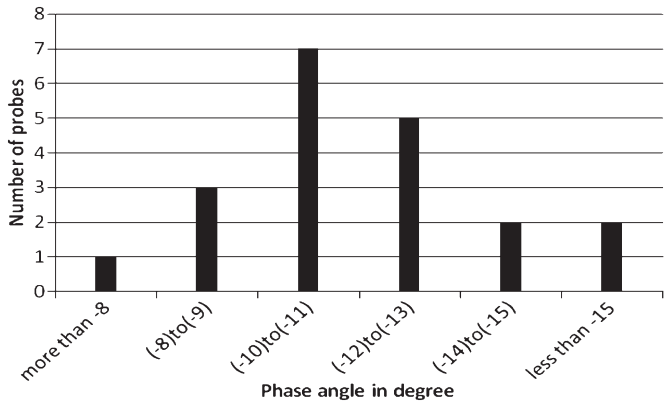

Fig. 6. Distribution of phase angle of 6-μm FOE with 2 cm in pH 4.0 solution.

The average size of the pores (assuming that the pores are circular) thus formed is 0.385 μm, and the number of pores per 100 μm^2 is 14. It is worth to mention that the FESEM images of the probe show that the phase angle deviation with the same coating thickness may result due to the difference in the distribution patterns of pores during the formation of the coating, even though the pore size and the number of pores per 100 μm^2 may approximately remain the same.

B. Characterization of Identical FOE

To study the characteristics and verify the performance of the FOEs, 20 probes (out of 22 shown in Table III) with 6 μm coating thickness are considered and dipped 2 cm in pH 4.0 buffer solution. The magnitude and phase angle of all 20 FOEs (numbered as FOE1 to FOE20) have been recorded (five times) as mentioned in Section II. The histogram plots in Fig. 6 present the distribution of the average value of the phase angle over the frequency range of 20–200 kHz, where FOEs have CPA. From Fig. 6, it is observed that, out of these 20 FOEs, seven have the CPA between -11° and -10°, five FOEs have CPA between -13° and -12°, while three FOEs show CPA between -8° and -9° and two FOEs show CPA between -14° and -15°. Moreover, a total of three FOEs exhibit a phase angle either more than -8° or less than -15°.

To measure the variability of the data set, the average of the absolute deviations of data points from their mean has been

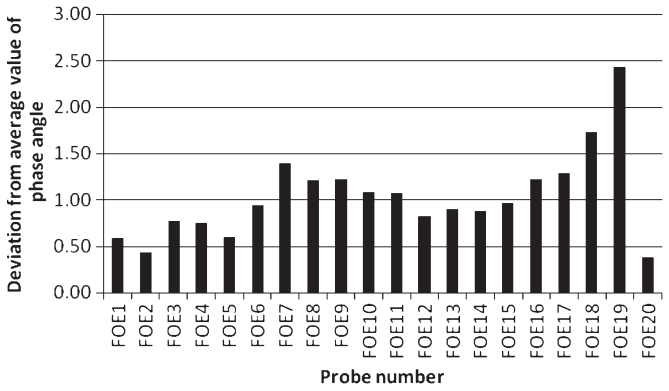

Fig. 7. Deviation from average value of its phase angle of 6-μm FOE with 2 cm in pH 4.0 solution.

TABLE IV
VALUES OF α AND Q OBTAINED FOR 12 FOEs

Probe No.	α	Deviation of α from average	Q	Deviation of Q from average
FOE7	0.11	0.015	780.5	20.1
FOE8	0.11	0.013	872.6	17.4
FOE9	0.11	0.013	811.6	20.8
FOE1	0.12	0.006	898.2	8.2
FOE2	0.12	0.005	884.3	13.3
FOE13	0.12	0.010	955.0	23.1
FOE14	0.12	0.010	1081.4	24.4
FOE3	0.13	0.008	878.9	11.9
FOE4	0.13	0.008	888.0	9.1
FOE15	0.13	0.011	1100.8	28.3
FOE16	0.13	0.014	1090.2	28.8
FOE17	0.14	0.014	1325.2	31.4

calculated and plotted as the bar graph in Fig. 7 for each FOE within the observed frequency range.

Lesser value in deviation indicates that a particular FOE has CPA within the prescribed frequency range.

From Fig. 7, 11 FOEs have deviation less than 1°, seven FOEs have deviation less than 1.5°, and two FOEs have more than 1.5°.

C. To Find Parameters Q and α of the Identical FOEs

The previous sections report a methodology to obtain the porous film on the electrodes and, thereafter, analysis on realizing FOE with them. Next, the values of the parameters, Q and α, of the FOE, as depicted in "(1)," have been calculated from the corresponding average value of the magnitude and phase angle for those 12 FOEs, which give CPA in between -10° and -13° in the frequency range of 20–200 kHz and tabulated in Table IV. The graphical representations of the parameters Q and α (for all the 12 probes) are shown in Figs. 8 and 9, respectively.

From Table IV, it is observed that the value of α is within 0.11 to 0.13, rounded to two decimal places for all the probes except for FOE17, and the deviations are also insignificant.

The value of Q is around 930 with the deviation around ± 45 except for probe number FOE17. From Fig. 8, it may be said that the change of α with frequency is almost constant,

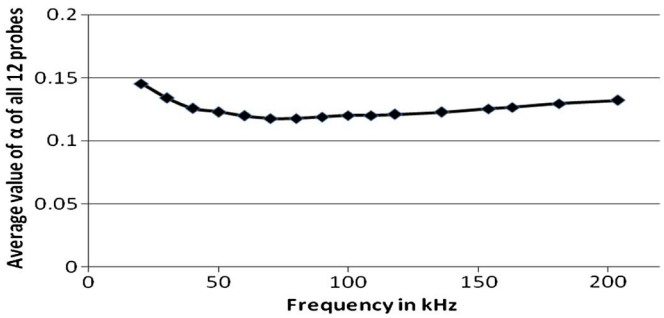

Fig. 8. Value of fractional exponent (α) with frequency for 6-μm FOE with 2 cm in pH 4.0 solution.

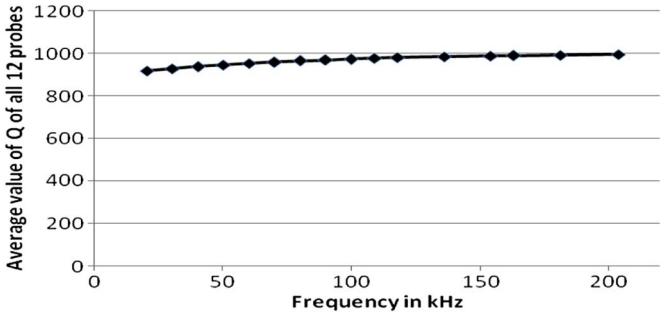

Fig. 9. Parameter Q with frequency for 6-μm FOE with 2 cm in pH 4.0 solution.

the variation remains within 0.01, and the change of Q is also negligible as observed in Fig. 9.

IV. CONCLUSION

The fabrication of a fractional order capacitor (named here as FOE) with desired specification has been reported in this paper. The emphasis was on identifying different parameters which will lead to realize a required FOE with predefined specifications. It has been shown that the manufacturing process plays an important role to develop the FOE which has been studied and elaborately discussed.

In this paper, the target was to achieve the value of fractional exponent α near 0.1 in a workable frequency range to make the device as a small-size single element suitable for day-to-day use in electrical circuit realization. For this, the packaged FOE, as shown in Fig. 2, is used, which has a bandwidth in the frequency zone of 20–200 kHz. It would not be out of place to mention that FOEs realized by this method show better performance in comparison with cross-ladder network and comparable performance with domino ladder network as observed in [17].

From Table I, it is apparent that, when the rotor speed is 600 r/min and the spin time is 120 s, 70% of the probes give 6 μm porous films on the electrodes. Adopting the same procedure, it has also been shown that 22 out of 35 probes result in 6-μm film thicknesses (see Table IV) which is more than 60%. Therefore, it is possible to get probes of different coating thicknesses by controlling the speed of the rotor, and also, repeatability is ensured.

The result summarized in Table IV and the graph of Fig. 8 show that the value of the exponent for the individual FOE

TABLE V
PARAMETERS USED FOR OBTAINING A COATING THICKNESS OF 5 TO 7 μm

Properties of PMMA	Density	1.178 gm/cm^3
	Resistivity	7×10^{12} ohm-cm
	Molecular Weight	3626.32
	Viscosity of 5 % conc. of PMMA-chloroform solution	11.10 cP

remains almost constant in the entire frequency zone. Twelve probes with 6 μm coating film show $\alpha = 0.12 \pm 0.01$, and for the second parameter of the FOE, i.e., Q, the value is 930$\pm$45 except for FOE17. Moreover, the results summarized in Table II and graphs 3 and 4 reveal that the values of Q and α are truly dependent on its phase angle which is again dependent on the thickness of the porous film over the metallic surface. From the FESEM images of the probe, it may be said that the phase angle deviation with the same coating thickness appears due to the difference in the distribution patterns of pores. It would be worth to mention here that the pores of the coating film allow the ions of the medium to diffuse into the electrode which is anomalous in nature, and its porosity dictates the value of the exponent α. Hence, the coating thickness which determines the porous nature of the film is the root cause to fabricate the desired FOE. However, by adjusting the factors such as the nature of the polarizable medium and the area of contact of the probe with the polarizable medium, tuning of α can be achieved.

Therefore, finally, it can be said that the aforementioned methodology is successful to reproduce a FOE with desired specifications. Research is going on to relate the nature of the dependence of α on t, A, and σ which needs an extensive experimental study and also to increase the bandwidth of operation.

APPENDIX

To study the properties of PMMA, different qualities of PMMA have been purchased from open market and used to develop FOEs. It has been observed that a particular type gives reproducible, uniform, and stable coating which has been used for fabrication of all the probes. To identify the properties of that PMMA, the density, resistivity, molecular weight (using differential scanning calorimetry, Model: Seiko DSC 6200), and viscosity of 5% PMMA in chloroform solution (using viscometer TV-10 of Toki Sangyo Company, Ltd.) have been measured. The properties measured are tabulated in Table V.

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