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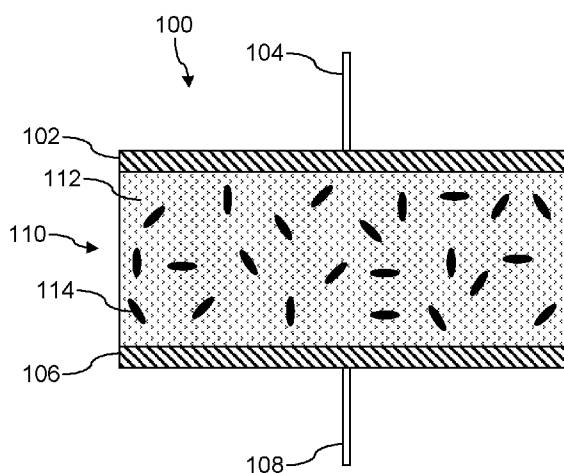


FIG. 1

(57) Abstract: A fractional order capacitor. The fractional order capacitor comprises a first conductive plate connected to a first connecting terminal, a second conductive plate connected to a second connecting terminal, and a composite dielectric disposed between the first plate and the second plate. The composite dielectric comprises a dielectric matrix material and filler particles, where the volume of the filler particles is less than 20% of the volume of the composite dielectric and where the filler particles comprise at least one transition metal dichalcogenide.

NUMERICAL DESIGN OF FRACTIONAL ORDER CAPACITORS

BACKGROUND

[0001] Fractional order capacitors (FOC) have impedance $Z(\omega) = \frac{1}{C(j\omega)^\alpha}$ where C is a constant that represents a capacitance, ω represents an angular frequency ($\omega = 2\pi f$), and α is a number in the range $0 < \alpha < 1$. Conventional capacitors have an α -value that is approximately 1. Such conventional capacitors may be referred to as “integer order” capacitors. It is understood, notwithstanding, that such conventional capacitors commonly exhibit an α -value of less than 1, but even low-quality conventional capacitors commonly exhibit an α -value > 0.95 . As such, conventional capacitors are often modeled as ideal integer order devices. The α -value of a capacitor may be sensitive to an operating frequency. Said in other words, FOCs may exhibit an α -value of approximately integer order, except in a predefined frequency band.

[0002] FOCs have applications in a variety of different fields that may be said to provide solutions to fractional order calculus problems. Some of these applications include solving nonlinear problems in such real-world domains as pattern recognition, automated control, signal processing, and modeling various processes. As one specific example, FOCs have application in proportional-integral-differential (PID) controllers. While fractional order calculus and FOCs have been studied theoretically, in practice it has been difficult to realize practical FOCs. Previous FOC realization approaches have involved liquid-electrode based (LEB) type FOCs, fractal-type (FT) FOCs, and ladder network approximation FOCs composed of conventional resistors and capacitors (e.g., integer order capacitors). These previous FOC realization techniques have suffered from one or more significant drawbacks. One commonly encountered significant drawback of previous techniques of realizing FOCs has been undesirable restriction on the operational frequency range of FOC behavior and/or undesirable ripple in the α -value of the FOC over the operational frequency range.

SUMMARY

[0003] In an embodiment, a fractional order capacitor is disclosed. The fractional order capacitor comprises a first conductive plate connected to a first connecting terminal, a second conductive plate connected to a second connecting terminal, and a composite dielectric disposed between the first plate and the second plate. The

composite dielectric comprises a dielectric matrix material and filler particles, where the volume of the filler particles is less than 20% of the volume of the composite dielectric and where the filler particles comprise at least one material comprising a transition metal dichalcogenide.

[0004] In an embodiment, a method of making a fractional order capacitor (FOC) is disclosed. The method comprises specifying a frequency range for fractional order capacitor behavior, specifying a phase angle of fractional order capacitor behavior, providing a list of filler materials and data on their permittivity and conductivity, and providing a list of dielectric matrix materials and data on their permittivity. The method further comprises determining a fitness function value for each of a plurality of different candidate fractional order capacitor designs by an application executing on a computer, where each design defines a fill fraction for filler materials, identifies a filler material, and identifies a dielectric matrix material and where the fitness function value is determined based on evaluating the phase angle of the candidate design at each of a plurality of frequencies within the specified frequency range for fractional order capacitor behavior, obtaining different candidate fractional order capacitor designs by the application in part using a genetic algorithm and based on the fitness function value of some candidate fractional order capacitor designs, selecting a candidate fractional order capacitor design by the application based on the fitness function value determined for that candidate. The method may further comprise creating instructions for making a composite dielectric comprised of the dielectric matrix material and the filler material based on the selected candidate fractional order capacitor design and manufacturing a fractional order capacitor based at least in part on the instructions for making the composite dielectric.

[0005] In another embodiment, a method of determining a design for a fractional order capacitor (FOC) is disclosed. The method comprises providing a list of filler materials and data on their permittivity and conductivity, where the list comprises molybdenum disulfide (MoS_2), molybdenum ditelluride (MoTe_2), tungsten disulfide (WS_2), tungsten diselenide (WSe_2), and single walled carbon nanotubes and providing a list of dielectric matrix materials and data on their permittivity, where the list comprises hafnium dioxide (HfO_2), hafnium silicate (HfSiO_4), zirconium dioxide (ZrO_2), and zirconium silicate (ZrSiO_4). The method further comprises determining a fitness function value for each of a plurality of different candidate fractional order capacitor designs, where each design defines a fill fraction for filler materials, identifies a filler

material, and identifies a dielectric matrix material and where the fitness function value is determined based on determining the phase angle of the candidate design at each of a plurality of frequencies within a predefined frequency range for fractional order capacitor behavior using a model for dielectric mixtures and comparing to a target phase angle. The method further comprises obtaining different candidate fractional order capacitor designs in part using a genetic algorithm and based on the fitness function value of some candidate fractional order capacitor designs, and selecting a candidate fractional order capacitor design based on the fitness function value determined for that candidate. In an embodiment, the method may further comprise creating instructions for making a composite dielectric composed of the dielectric matrix material and the filler material based on the selected candidate fractional order capacitor design. In an embodiment, the method may further comprise manufacturing a fractional order capacitor based at least in part on the instructions for making the composite dielectric.

[0006] In yet another embodiment, a method of determining a design for a fractional order capacitor (FOC) is disclosed. The method comprises specifying a frequency range for fractional order capacitor behavior, specifying a phase angle of fractional order capacitor behavior, and providing a list of dielectric materials and data on their permittivity. The method further comprises selecting a first and a second dielectric material from the list of dielectric materials by an application executing on a computer system based on the specified phase angle, based on the specified frequency range, based on the data on the permittivity of the first dielectric material, and based on the data on the permittivity of the second dielectric material, determining a thickness of a composite dielectric layer of the fractional order capacitor design by the application based on determining a first thickness of the first dielectric material and a second thickness of the second dielectric material, where the thickness of the composite dielectric layer is based on the sum of the first and second thickness, where the first and second thicknesses are determined to achieve the specified phase angle of the fractional order capacitor over the specified frequency range of fractional order behavior, and creating instructions for making the fractional order capacitor based on the selected dielectric materials, the first thickness, and the second thickness.

[0007] These and other features will be more clearly understood from the following detailed description taken in conjunction with the accompanying drawings and claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] For a more complete understanding of the present disclosure, reference is now made to the following brief description, taken in connection with the accompanying drawings and detailed description, wherein like reference numerals represent like parts.

[0009] FIG. 1 is an illustration of a fractional order capacitor having a composite dielectric according to an embodiment of the disclosure.

[0010] FIG. 2 is an illustration of a fractional order capacitor having a layered dielectric according to another embodiment of the disclosure.

[0011] FIG. 3 is an illustration of a fractional order capacitor having a layered dielectric according to yet another embodiment of the disclosure.

[0012] FIG. 4 is a flow chart of a method according to an embodiment of the disclosure.

[0013] FIG. 5 is a flow chart of another method according to an embodiment of the disclosure.

[0014] FIG. 6 is a flow chart of yet another method according to an embodiment of the disclosure.

[0015] FIG. 7 is a block diagram of a computer system according to an embodiment of the disclosure.

DETAILED DESCRIPTION

[0016] It should be understood at the outset that although illustrative implementations of one or more embodiments are illustrated below, the disclosed systems and methods may be implemented using any number of techniques, whether currently known or not yet in existence. The disclosure should in no way be limited to the illustrative implementations, drawings, and techniques illustrated below, but may be modified within the scope of the appended claims along with their full scope of equivalents.

[0017] The present disclosure teaches a fractional order capacitor (FOC) device, a method for making an FOC, and a method for designing an FOC based on a performance specification of the FOC. The FOC device comprises two conductive plates and a composite dielectric. The composite dielectric may be designed using the method for designing an FOC taught herein. In an embodiment, the composite dielectric may comprise a dielectric matrix material and filler particles. The filler particles comprise less than about 20% by volume of the composite dielectric. Said in another way, the filler particles are present in a concentration below the percolation threshold of the composite dielectric. The filler particles may comprise semiconductor

material. The filler particles may comprise at least one material comprising a transition metal dichalcogenide. The filler particles may comprise two or more different transition metal dichalcogenides. The filler particles may comprise a mix of graphene particles and particles comprising a material comprising a transition metal dichalcogenide. The filler particles may comprise a mix of transition metal dichalcogenide material at different dopant levels, for example a mix of a first transition metal dichalcogenide material at a first dopant level and the first transition metal dichalcogenide material at a second dopant level. For example, the filler particles may comprise a mix of molybdenum disulfide (MoS_2) particles having a first dopant level and MoS_2 particles having a second dopant level. The method of making an FOC may embed within it steps of designing an FOC based on an input performance specification of the FOC, where the input performance specification may comprise a desired phase angle and an operational frequency range for the FOC. The method for designing the FOC will determine an FOC design which satisfies the performance specification. Designing the FOC may be implemented, in part, as an application or computer program that executes on a computer.

[0018] The FOC design comprises conventional terminals, conventional plates, and a designed composite dielectric, where the composite dielectric promotes the fractional order behavior of the capacitor. It is understood that the FOC design may be implemented and manufactured in a variety of different forms. The conductive plates may be implemented as two sheets of metallic foil that are separated by the composite dielectric and rolled up to form a cylindrical shape. The conductive plates may be implemented as metal layers in a semiconductor manufacturing process where multiple layers are built up successively. For example, a first conductive layer may be deposited on a semiconductor substrate, the composite dielectric may be deposited on top of the first conductive layer, and a second conductive layer may be deposited on top of the composite dielectric. In embodiment, after the composite dielectric is deposited on top of the first conductive layer, a plurality of planar metal regions may be deposited on top of the composite dielectric, forming a plurality of FOCs with a shared first conductive plate (first conductive layer), a shared composite dielectric, and separate second conductive plates for each separate capacitor.

[0019] In general, the composite dielectric may be composed of a dielectric matrix material mixed with one or more filler materials different from the matrix material, where the filler materials are provided in a ratio that is below a percolation threshold of the

composite dielectric (e.g., is provided in a dilute regime or in a relatively sparse amount). In an embodiment, the percolation threshold of the composite dielectric may be less than about 20% of the volume of the composite dielectric comprises filler materials. In an embodiment, the percolation threshold of the composite dielectric may be less than about 15% of the volume of the composite dielectric comprises filler materials. In an embodiment, the percolation threshold of the composite dielectric may be less than about 10% of the volume of the composite dielectric comprises filler materials. In an embodiment, the percolation threshold of the composite dielectric may be some other percentage of filler materials. The filler material may be supplied as small particles that are suspended in the dielectric matrix material to form the composite dielectric). Alternatively, the composite dielectric may be composed of layers of dielectric materials where each layer is composed of a different dielectric material.

[0020] In an embodiment, the dielectric matrix material may be selected from high-k dielectric materials (e.g., a material with a high dielectric constant) such as hafnium dioxide (HfO_2), hafnium silicate (HfSiO_4), zirconium dioxide (ZrO_2), or zirconium silicate (ZrSiO_4). The dielectric matrix material may be selected from one or more polymers, such as polyvinylidene fluoride (PVDF). In an embodiment, the filler materials may be selected from transition metal dichalcogenide semiconductor materials such as molybdenum disulfide (MoS_2), molybdenum ditelluride (MoTe_2), tungsten disulfide (WS_2), and/or tungsten diselenide (WSe_2). Alternatively, single walled carbon nanotubes, which exhibit semiconductor-like behavior, may also be used as filler materials. Each filler material, for example MoS_2 , may be differentiated by the inclusion of dopants in the base semiconductor material. Thus, MoS_2 incorporated in the composite dielectric may comprise a plurality of different filler materials differentiated by different dopant concentration levels. For example, the filler material in the composite dielectric of the FOC may comprise a first plurality of particles of MoS_2 at a first dopant concentration level, a second plurality of particles of MoS_2 having a second dopant concentration level, and a third plurality of particles of MoS_2 having a third dopant concentration level. By choosing a dielectric matrix material and choosing one or more different filler materials, a design can be determined for an input desired phase angle and an input desired frequency band. Said in other words, the design process can tune the FOC in both the phase angle and the frequency band at the same time.

[0021] The application executing on the computer identifies a plurality of candidate FOC designs, evaluates the phase angle associated with each candidate FOC design

across the predefined frequency band, and determines a fitness value of each design based on the extent to which the phase angle evaluated across the predefined frequency range approaches a predefined or target phase angle. The application may evaluate the phase angle at a frequency based on estimating the phase angle using a mathematical model that employs the candidate FOC design parameters as an input. Based on the determined fitness values, some candidate FOC designs may be rejected, and other candidate FOC designs may be retained for recombining and mutating according to a genetic algorithm to provide “children” candidate FOC designs to be evaluated in a second iteration of the genetic algorithm. At the end of the genetic algorithm, the candidate FOC design whose fitness value best satisfies the fitness criteria may be selected as the final FOC design.

[0022] A candidate FOC design may correspond to a “chromosome” in the genetic algorithm, and individual elements of the design may correspond to a “gene” in the genetic algorithm. The elements of the candidate FOC designs that correspond to the “genes” comprise the electrical characteristics of each of one or more filler material and its fractional portion of the composite dielectric. For example, a candidate FOC design may comprise a first MoS₂ filler material that is undoped and exhibits a first conductivity and having a fill fraction of 1%, a second MoS₂ filler material that is doped at a first dopant concentration level and exhibits a second conductivity and having a 3% fill fraction, and a third MoS₂ filler material that is doped at a second dopant concentration level and exhibits a third conductivity and having a 2% fill fraction. Thus, this “chromosome” may comprise 6 “genes.”

[0023] Adding more filler materials, for example different versions of the same base filler material each having different dopant concentration levels, is a technique that can broaden the frequency bandwidth in which the phase angle of the FOC satisfies the input desired phase angle. Adapting or tuning the conductivity of filler material versions by adapting dopant levels can adjust a ripple or variation of the phase angle in the specified frequency bandwidth. Adjusting the fill fraction of filler materials can adjust the amplitude of the phase angle. Thus, by selecting dielectric matrix materials, selecting filler materials, adapting fill fractions, and adapting conductivity of filler materials (e.g., by adapting dopant concentration levels), the designed FOC can be tuned or designed to both achieve a predefined or target phase angle and achieve a predefined frequency bandwidth. In an embodiment, an aspect ratio of filler materials may be selected to further adapt the characteristic behavior of the composite dielectric. For example, the

shape of filler materials can be varied between oblate to spherical to prolate. For further information about fractional order capacitors, see U.S. Provisional Patent Application 62/487,467, filed this same day April 19, 2017, titled "Modeling a Fractional Order Capacitor Design," by Khaled Nabil Salama, *et al.*, U.S. Provisional Patent Application 62/487,468, filed this same day April 19, 2017, titled "Phase Angle Tunable Fractional-order Capacitors Including Poly (Vinylidene Fluoride)-based Polymers and Blends and Methods of Manufacture Thereof," by Khaled Nabil Salama, *et al.*, and U.S. Provisional Patent Application 62/487,463, filed this same day April 19, 2017, titled "Phase Angle Tunable Fractional-order Capacitors Including Multi-layer Dielectric Layers Methods of Manufacture Thereof," by Khaled Nabil Salama, *et al.*, which are hereby incorporated by reference, each in its entirety.

[0024] Turning now to FIG. 1, a first fractional order capacitor (FOC) 100 is described. In an embodiment, the FOC 100 comprises a first plate 102 connected to a first terminal 104, a second plate 106 connected to a second terminal 108, and a composite dielectric 110. It is understood that the illustration of the FOC 100 is not intended to represent a relative scale or a particular realization form. In an embodiment, an FOC may be realized as two extended metal ribbons sandwiching an extended composite dielectric ribbon, which are then rolled up tightly to form a cylindrical shape. Alternatively, other realizations of FOCs, that are manufactured using different assembly and construction approaches, may advantageously apply the teachings of the present disclosure. For example, the FOC may be built as a component of a semiconductor chip, for example deposited on a semiconductor die using semiconductor manufacturing processes, or as a component of a system on a chip (SOC).

[0025] The composite dielectric 110 comprises a dielectric matrix 112 and a plurality of filler particles 114. The shapes and orientations of the filler particles 114 are depicted in FIG. 1 to suggest that they may be disposed with random orientations within the dielectric matrix 112. Also, while the filler particles 114 are illustrated as elongated (either oblate or prolate, depending on the reference axis of the particles) in FIG. 1, in an embodiment, the filler particles 114 may have a different aspect ratio (e.g., spherical). In an embodiment, the composite dielectric 110 may comprise a mix of filler particles 114 of different aspect ratios. The filler particles 114 may be very small, for example less than 100 μm in length, less than 10 μm in length, less than 1 μm in length, less than 100 nm in length, or some other size.

[0026] Part of the design of a capacitor, including the design of a fractional order capacitor, may involve designing a separation between the plates 102, 106 and a surface area of the plates 102, 106. While the separation and area of the plates 102, 106 may be designed to realize the FOC 100, this may be deemed a conventional design parameter. Therefore, this disclosure will not comment further or teach how to design the separation and area of the plates 102, 106. Instead, the disclosure focuses on the numerical design of the composite dielectric 110 which determines the specific characteristic of the fractional order behavior of the FOC 100.

[0027] The phase angle of an FOC at a given frequency is a function of an effective permittivity of the composite dielectric 110:

$$\varphi = F(\varepsilon_{eff})$$

(EQ 1)

where φ is the phase angle and ε_{eff} is the effective permittivity of the composite dielectric 110 at the given frequency. The effective permittivity can be thought of as the aggregate permittivity of the composite dielectric 110. Permittivity is a fundamental physical property of matter generally, and of dielectrics in specific, that is a measure of how an electric field affects and is affected by the material. The effective permittivity of the composite dielectric 110 can be determined using an effective medium approximation model, for example using the Bruggeman's model, the Maxwell-Garnett mixing rule, or using another approximation model or equation.

[0028] The effective permittivity of the composite dielectric 110 at a given frequency is a function of a permittivity of the dielectric matrix material 112 at the given frequency, the permittivity of each of the different filler particles 114 at the given frequency, as well as the volume fractions (the fraction of the volume of the composite dielectric) occupied by each of the filler particles 114:

$$\varepsilon_{eff} = F(\varepsilon_m, \varepsilon_1, \varepsilon_2, \dots, \varepsilon_n, f_1, f_2, \dots, f_n)$$

(EQ 2)

where ε_m is the permittivity of the dielectric matrix material at the given frequency, ε_1 is the permittivity of the first filler material at the given frequency, ε_2 is the permittivity of the second filler material at the given frequency, ε_n is the permittivity of the n-th filler material at the given frequency, f_1 is the volume fraction occupied by the first filler

material, f_2 is the volume fraction occupied by the second filler material, and f_n is the volume fraction occupied by the n -th filler material. The effective permittivity of the composite dielectric 110 may also be a function of an aspect ratio (quantification of shape) of filler materials. It is understood that some of the permittivities may be independent of operational frequency, for example the permittivity of the dielectric matrix material 112 may be independent of operational frequency for some materials, but in general at least some of the permittivities of the components of the composite dielectric 110 (e.g., some of the filler particles 114) may be different at different frequencies.

[0029] The permittivity of a dielectric matrix material 112 may be a known physical property and may be provided as a physical constant for use by the application executing on the computer, for example provided as a table or list of data or embedded among a list of defined constant values within the application code. Likewise, the permittivity of undoped filler particles may be known physical properties and provided as a physical constant for use by the application. The permittivity of doped filler particles may be a function of the permittivity of the undoped filler material and the conductivity of the doped filler material:

$$\varepsilon_i = \varepsilon_{sc} + \frac{\sigma}{j\omega\varepsilon_0}$$

(EQ 3)

$$\sigma = q\mu n$$

(EQ 4)

where ε_{sc} is the permittivity of the undoped filler material ('sc' stands for semiconductor), σ is the conductivity of the doped filler material, ω is the angular frequency at the given frequency ($\omega = 2\pi(\text{frequency})$), ε_0 is the permittivity of free space, q is the charge of the charge carrier in the doped filler material, μ is the mobility of the charge carriers in the doped filler material, and n is the number of dopant concentration. In an embodiment, different methods or equations may be used to determine the permittivity of doped filler material. In an embodiment, a plurality of values of permittivity for a doped filler material at different dopant concentration levels may be

determined and provided in a look-up table or list of constants for the application, and doped filler materials that have intermediate dopant concentration levels may be determined by interpolating permittivity values of neighboring doped filler materials read from the look-up table or list of constants.

[0030] With reference again to determining the effective permittivity of the composite dielectric 110 (see **EQ 2**), a multiphase Maxwell-Garnett mixing rule may be used to estimate the effective permittivity. In one form, the multiphase Maxwell-Garnett mixing rule for purposes of this disclosure may be given:

$$\varepsilon_{eff} = \varepsilon_m + \left\{ \frac{\frac{1}{3} \left(\sum_{i=1}^n f_i (\varepsilon_i - \varepsilon_m) \sum_{j=x,y,z} \frac{\varepsilon_m}{\varepsilon_m + N_{ij} (\varepsilon_i - \varepsilon_m)} \right)}{1 - \frac{1}{3} \left(\sum_{i=1}^n f_i (\varepsilon_i - \varepsilon_m) \sum_{j=x,y,z} \frac{N_{ij}}{\varepsilon_m + N_{ij} (\varepsilon_i - \varepsilon_m)} \right)} \right\}$$

(EQ 5)

where ε_m is the permittivity of the dielectric matrix material, n is the number of different filler materials (not to be confused with the 'n' of EQ 4 which represents a different parameter), ε_i is the permittivity of the i -th filler material at the given frequency, f_i is the volume fraction occupied by the i -th filler material, and N_{ij} are the depolarization factors of the i -th filler material.

[0031] Equations EQ 1, EQ2, EQ3, EQ4, and EQ 5 may be used to develop algorithms in the application to determine the phase angle of the FOC 100 at each of a plurality of different frequencies. It is understood that the equations may be simplified and/or mathematically transformed to make computer solution of the equations more tractable and/or efficient. In some circumstances, some of the terms of the equations may be simplified. For example, when the filler materials 114 are spherical the depolarization factors N may all be equal and EQ 5 may be further simplified. For example, if the effect of depolarization factors N may be considered of negligible importance, EQ 5 may be further simplified. Additionally, some other technique than the Maxwell-Garnett mixing rule may be used to find the effective permittivity at different frequencies.

[0032] The application may determine the phase angle of the FOC 100 at a plurality of frequencies that lie within a predefined operational frequency range of the FOC 100 and possibly some frequencies outside the operational frequency range but neighboring the bottom of the range and neighboring the top of the range. The operational frequency range is the range of frequencies at which it is desired that the FOC 100 exhibit the target phase angle. This may be referred to as the constant phase zone (CPZ) of the FOC 100, notwithstanding that the phase angle may vary within that CPZ, for example within an allowed maximum and minimum phase angle or with a maximum ripple amplitude. It is noted in passing that the α -value mentioned above and the phase angle φ can be related by:

$$\alpha = \frac{-\varphi}{90}$$

(EQ 6)

The phase angle φ can be determined by:

$$\varphi = \tan^{-1} \left(\frac{\varepsilon_{real}}{\varepsilon_{imag}} \right)$$

(EQ 7)

where the numerator is the real part of ε_{eff} and the denominator is the imaginary part of ε_{eff} (it is understood that ε_{eff} is a complex number having both a real component or part and an imaginary component or part).

[0033] For purposes of this disclosure, to distinguish FOCs from non-ideal but still “integer order” capacitors, it is understood that a fractional order capacitor as described herein may have an α in the CPZ such that α is in a range defined by: $0 < \alpha < 0.95$ (i.e., $0 > \varphi > -85.5^\circ$), $0 < \alpha < 0.90$ (i.e., $0 > \varphi > -81^\circ$), or $0 < \alpha < 0.85$ (i.e., $0 > \varphi > -76.5^\circ$). Generally, non-ideal “integer-order” capacitors are understood to have $\alpha \geq 0.95$ (i.e., $\varphi \leq -85.5^\circ$). Thus, a first example FOC may have a CPZ of 100 MHz to 10 GHz and an $\alpha = 0.8 \pm 0.0167$ (i.e., $\varphi = -72^\circ \pm 1.5^\circ$) when operated within the CPZ. A second example FOC may have a CPZ of 10 MHz to 15 GHz and an $\alpha = 0.9 \pm 0.0333$ (i.e., $\varphi = -81^\circ \pm 3^\circ$) when operated within the CPZ. A third example FOC 100 may have a CPZ of 50 MHz to 2 GHz and an

$\alpha = 0.5 \pm 0.0222$ (i.e., $\varphi = -45^\circ \pm 2^\circ$) when operated within the CPZ. Another capacitor that has an $\alpha = 0.96 \pm 0.01$ (i.e., $\varphi = -86.4^\circ \pm 0.9^\circ$) would not be considered an FOC but rather a non-ideal “integer-order” capacitor.

[0034] The phase angle may be determined by the application executing on the computer system at some predefined number of frequencies within the predefined operational frequency range, for example at about 100 different frequencies, at about 500 different frequencies, at about 1,000 different frequencies, at about 5,000 different frequencies, or some other number of different frequencies. The frequencies at which the phase angle is to be determined may be distributed linearly across the predefined operational frequency range. For example, if a frequency range of 1 GHz is defined and the phase angle is to be determined for 1,000 different frequencies, the 1,000 different frequencies may be each separated by about 1 MHz (1000 x 1 MHz is 1 GHz). Alternatively the frequencies at which the phase angle is to be determined may be distributed in a non-linear way, for example logarithmically.

[0035] A fitness function may be defined for evaluating how well a candidate FOC design satisfies a set of predefined objectives or operational specifications of an FOC. This fitness function may involve comparing the phase angle of the candidate FOC design calculated at each of a plurality of frequencies to the specified target phase angle and determining a fitness metric that represents the aggregate amount of agreement between the target phase angle and each of the frequency-dependent calculated phase angles. In an embodiment, the fitness function may have the general form of:

$$Fitness = \sum_{r=1}^k (\varphi_{target} - \varphi_r)^2$$

(EQ 8)

where k is the number of different frequencies at which the phase angle is to be determined, φ_{target} is the predefined or target phase angle, and φ_r is the phase angle of the FOC determined at the r -th frequency. The fitness metric defined by EQ 8 is a sum of squares of differences. Because each difference is squared, each term of the sum will be a positive value. The closer the phase angle of the candidate FOC design is to the target phase angle, at a given frequency, the smaller the square of the difference will be. Thus, generally speaking, a lower numerical value of the fitness

metric of EQ 8 corresponds to a better match of the corresponding candidate FOC design to the specification of the desired FOC performance.

[0036] A ripple amplitude for a candidate FOC design can be calculated by identifying maximum phase angle and minimum phase angle at different frequencies across the frequency operating range (i.e., identify local maxima and local minima of phase angle). A specification for an FOC design may stipulate that the successful FOC design meet both the frequency operating range specification and a maximum ripple amplitude over the frequency operating range specification.

[0037] The application may proceed by proposing a plurality of FOC design candidates, determining a fitness of each of the design candidates, rejecting some of the candidates, and creating a second generation of FOC design candidates based on the retained candidates. For example, a genetic algorithm may be used to “mate” characteristics of fitter “parent” FOC design candidates to create “child” FOC design candidates to evaluate. By selecting “parents” from the fitter FOC design candidates (e.g., having a fitness metric at or above a median fitness metric determined for a “generation” of FOC design candidates), the genetic algorithm may converge on a successively more fit generation of FOC design candidates. The genetic algorithm iteratively creates a new generation of FOC design candidates, calculates the fitness metric on those candidates, selects fitter parents for the subsequent generation, and creates that subsequent generation from the parents. A “mutation” mechanism may also provide for some variation of “child” FOC design candidate “genes” from the set of “genes” present in the parents. The application may terminate the genetic algorithm when an FOC design candidate is determined to have a fitness value that satisfies a fitness criteria (e.g., is less than a threshold value). The application may terminate after a maximum number of iterations, choosing the best FOC design candidate based on the fitness criteria and fitness evaluations.

[0038] After choosing an FOC design candidate, the FOC design may be translated into a set of manufacturing instructions or a “recipe” for making the FOC 100. In an embodiment, the manufacturing instructions may restrict themselves to defining the composition of the composite dielectric 110, for example by identifying the dielectric matrix material 112, defining the filler material 114 or filler materials, and defining a volume fraction of the one or more filler materials 114. The manufacturing instructions may define a dopant concentration level of one or more of the filler materials 114. In another embodiment, the manufacturing instructions may further define a thickness of

the composite dielectric 110 (e.g., define a separation of the plates 102, 106 from each other) and define an area of the plates 102, 106. The definition of the area of the plates 102, 106 may be provided as a length and a width of the plates 102, 106. It may be understood that the composite dielectric 110 may have a length and a width substantially equal to that defined for the plates 102, 106, for example some small increment less wide and some small increment less long than the plates 102, 106 or possibly a small increment wider and longer than the plates 102, 106. The FOC 100 may be built in accordance with the manufacturing instructions. It is understood that some aspects of the manufacturing of the FOC 100 may be determined separately. For example, the length, cross-sectional area, and material of the terminals 104, 108 may be independently determined or defined. A packaging of the FOC 100 may be determined separately.

[0039] Turning now to FIG. 2, another embodiment of an FOC 130 is described. In an embodiment, the FOC capacitor 130 comprises the first plate 102, the first electrical terminal 104, the second plate 106, and the second terminal 108, and a composite dielectric 132. The composite dielectric 132 comprises a first dielectric layer 134 of thickness T_1 and a second dielectric layer 136 of thickness T_2 . In some contexts, the composite dielectric 132 may be referred to as a layered dielectric. The first dielectric layer 134 comprises a first dielectric material having a first frequency-dependent permittivity. The second dielectric layer 136 comprises a second different dielectric material having a second different frequency-dependent permittivity. Over a pre-defined Constant Phase Zone (CPZ) of the FOC 130 the effective permittivity of the composite dielectric 132, and hence the phase angle φ of the FOC 130, is an intermediate value between the first frequency-dependent permittivity of the first dielectric layer 134 and the second frequency-dependent permittivity of the second dielectric layer 136. By adapting the thicknesses T_1 and T_2 , a separation between the plates 104, 106 can be defined (i.e., separation = $T_1 + T_2$), which influences the capacitance of the FOC 130, and the proportional relationship between T_1 and T_2 can be defined, which modulates the effective permittivity between the first and second permittivities. For example, if T_1 is increased while T_2 is decreased, the effective permittivity is moved closer to the first frequency-dependent permittivity of the first dielectric layer 134 and further away from the second frequency-dependent permittivity of the second dielectric layer 136. If T_2 is increased while T_1 is decreased, instead, the effective permittivity moves closer to the second frequency-dependent permittivity of the

second dielectric layer 136 and further away from the first frequency-dependent permittivity of the first dielectric layer 134. The effective permittivity of the composite dielectric 132 may be determined as:

$$\varepsilon_{eff} = \left(1 + \left(T_2/T_1\right)\right) \left\{ \frac{1}{\varepsilon_1} + \frac{\left(T_2/T_1\right)}{\varepsilon_2} \right\}^{-1}$$

(EQ 9)

where T_1 is the thickness of the first dielectric layer 134, T_2 is the thickness of the second dielectric layer 136, ε_1 is the permittivity of the first dielectric layer 134, and ε_2 is the effective permittivity of the second dielectric layer 136.

[0040] The application that executes on the computer can design the FOC 130 based on a specification of desired performance of the FOC 130, for example a specified phase angle, a maximum phase angle ripple amplitude (or a maximum and minimum specification of allowed phase angle), and an operational frequency bandwidth or constant phase zone. The application may have a list of available dielectric materials for composing the layers 134, 136. The application may be provided with a function or formula for determining the frequency-dependent permittivity of the different available dielectric materials. The application may have a function for determining the effective permittivity of the composite dielectric 132 at a given frequency based on the permittivity of each dielectric layer 134, 136 at the given frequency, based on T_1 , and based on T_2 . The application may not use a genetic algorithm to determine the design of the FOC 130.

[0041] After determining a design for the FOC 130, the FOC design may be translated into a set of manufacturing instructions or a “recipe” for making the FOC 130. In an embodiment, the manufacturing instructions for making the FOC 130 may restrict themselves to defining the dielectric materials 134, 136 used and the thicknesses T_1 and T_2 . In another embodiment, the manufacturing instructions may further define an area of the plates 102, 106. The definition of the area of the plates 102, 106 may be provided as a length and a width of the plates 102, 106. It may be understood that the composite dielectric 132 may have a length and width substantially equal to that defined for the plates 102, 106, for example some small increment less wide and some small increment less long than the plates 102, 106 or possibly a small increment wider and

longer than the plates 102, 106. The FOC 130 may be built in accordance with the manufacturing instructions. It is understood that some aspects of the manufacturing of the FOC 130 may be determined separately. For example, the length, cross-sectional area, and material of the terminals 104, 108 may be independently determined or defined. A packaging of the FOC 130 may be determined separately.

[0042] Turning now to FIG. 3, another embodiment of an FOC 150 is described. In an embodiment, the FOC capacitor 130 comprises the first plate 102, the first electrical terminal 104, the second plate 106, and the second terminal 108, and a composite dielectric 152. The composite dielectric 152 comprises a third dielectric layer 154 of thickness T_3 , a fourth dielectric layer 156 of thickness T_4 , and a fifth dielectric layer 158 of thickness T_5 . In some contexts, the composite dielectric 152 may be referred to as a layered dielectric. The third dielectric layer 154 comprises a third dielectric material having a third frequency-dependent permittivity. The fourth dielectric layer 156 comprises a fourth different dielectric material having a fourth different frequency-dependent permittivity. The fifth dielectric layer 158 comprises a fifth different dielectric material having a fifth different frequency-dependent permittivity. Over a pre-defined CPZ of the FOC 150 the effective permittivity of the composite dielectric 152, and hence the phase angle φ of the FOC 150, is a value intermediate between extremes of the third frequency-dependent permittivity of the third dielectric layer 154, the fourth frequency-dependent permittivity of the fourth dielectric layer 156, and the fifth frequency-dependent permittivity of the fifth dielectric layer 158. By adapting the thicknesses T_3 , T_4 , and T_5 , a separation between the plates 104, 106 can be defined (i.e., separation = $T_3 + T_4 + T_5$), which influences the capacitance of the FOC 150, and the relationships among T_3 , T_4 , and T_5 can be defined, which modulates the effective permittivity. By adding a third dielectric material a sensitivity of the design of the FOC 150 to manufacturing variances in building the layers 154, 156, 158 (deviation from the specified design values of T_3 , T_4 , and T_5) may be reduced. For example, a dielectric material may be chosen that is closest to a design effective permittivity. This dielectric material may be used to make the thickest layer of the composite dielectric 152. The thickness of the other two dielectric materials may be adapted to adjust the phase angle of the composite dielectric 152 in a desirable sense, for example to extend the operational frequency bandwidth (e.g., CPZ) or to increase or decrease the phase angle.

[0043] The effective permittivity of the composite dielectric 152 may be determined by applying EQ 8 twice. For example, EQ 8 may be used to find the effective permittivity of the third dielectric layer 154 and the fourth dielectric layer 156. Then, this effective permittivity may be substituted for the first permittivity, and the sum of the thicknesses T_3 and T_4 substituted for the first thickness in EQ 8 and the permittivity of the fifth dielectric layer 158 substituted for the second permittivity and the thickness T_5 substituted for the second thickness used in EQ 8.

[0044] After determining a design for the FOC 150, the FOC design may be translated into a set of manufacturing instructions or a “recipe” for making the FOC 150. In an embodiment, the manufacturing instructions for making the FOC 150 may restrict themselves to defining the dielectric materials 154, 156, and 158 used and the thicknesses T_3 , T_4 , and T_5 . In another embodiment, the manufacturing instructions may further define an area of the plates 102, 106. The definition of the area of the plates 102, 106 may be provided as a length and a width of the plates 102, 106. It may be understood that the composite dielectric 152 may have a length and width substantially equal to that defined for the plates 102, 106, for example some small increment less wide and some small increment less long than the plates 102, 106 or possibly a small increment wider and longer than the plates 102, 106. The FOC 150 may be built in accordance with the manufacturing instructions. It is understood that some aspects of the manufacturing of the FOC 150 may be determined separately. For example, the length, cross-sectional area, and material of the terminals 104, 108 may be independently determined or defined. A packaging of the FOC 150 may be determined separately.

[0045] Turning now to FIG. 4, a method 200 is described. Method 200 may be performed to design a fractional order capacitor, for example the FOC 100 described above with reference to FIG. 1. At block 202, specify a frequency range for fractional order capacitor behavior. At block 204, specify a phase angle of fractional order capacitor behavior. The processing of blocks 202 and 204 may be performed by a technician or engineer entering these values to a workstation or computer console that presents an interface of an FOC design application that executes on a computer. At block 206, provide a list of filler materials and data on their permittivity and conductivity. At block 208, provide a list of dielectric matrix materials and data on their permittivity. In an embodiment, the list of materials and associated data may be provided as a data file or configuration file accessed by the FOC design application. For example, the data file

or configuration file may be stored in a non-volatile memory of the computer or in a secondary storage that is communicatively coupled to the computer. Alternatively, the list of materials and associated data may be provided in the coding of the FOC design application, for example as constant value definitions and/or as lines of executable code.

[0046] At block 210, an application executing on a computer determines a fitness function value for each of a plurality of different candidate fractional order capacitor designs, where each design defines a fill fraction for filler materials, identifies a filler material, and identifies a dielectric matrix material and where the fitness function value is determined based on evaluating the phase angle of the candidate design at each of a plurality of frequencies within the specified frequency range for fractional order capacitor behavior. The application may be the FOC design application. Computers are further discussed herein after. At block 212, the application obtains different candidate fractional order capacitor designs by the application in part using a genetic algorithm and based on the fitness function value of some candidate fractional order capacitor designs. The processing of blocks 210 and 212 may be repeated a plurality of times, for example to promote the genetic algorithm to successively converge on fitter and fitter design candidates. The iteration may finish when the fitness metric of a candidate design satisfies a fitness criteria (e.g., the fitness metric is lower than a predefined value) or when a pre-defined number of iterations have been completed. At block 214, the application selects a candidate fractional order capacitor design based on the fitness function value determined for that candidate.

[0047] In an embodiment, the method 200 may further comprise creating a set of fractional order capacitor manufacturing specifications or instructions, based on the selected fractional order capacitor design selected in block 214, that may be handed off to a manufacturing facility. At block 216, the method 200 may further comprise manufacturing or building a fractional order capacitor according to the specifications or instructions.

[0048] Turning now to FIG. 5, a method 230 is described. Method 230 may be performed to design a fractional order capacitor, for example FOC 100 described above with reference to FIG. 1. At block 232, provide a list of filler materials and data on their permittivity and conductivity, where the list comprises molybdenum disulfide (MoS_2), molybdenum ditelluride (MoTe_2), tungsten disulfide (WS_2), tungsten diselenide (WSe_2), and single walled carbon nanotubes. At block 234, provide a list of dielectric matrix

materials and data on their permittivity, where the list comprises hafnium dioxide (HfO_2), hafnium silicate (HfSiO_4), zirconium dioxide (ZrO_2), and zirconium silicate (ZrSiO_4). The lists and data of blocks 232, 234 may be provided to an FOC design application from a configuration file or may be embedded in code that implements the application.

[0049] At block 236, determine a fitness function value for each of a plurality of different candidate fractional order capacitor designs by an application executing on a computer, where each design defines a fill fraction for filler materials, identifies a filler material, and identifies a dielectric matrix material and where the fitness function value is determined based on determining the phase angle of the candidate design at each of a plurality of frequencies within a predefined frequency range for fractional order capacitor behavior using a model for dielectric mixtures and comparing to a target phase angle. At block 238, obtain different candidate fractional order capacitor designs by the application in part using a genetic algorithm and based on the fitness function value of some candidate fractional order capacitor designs. At block 240 select a candidate fractional order capacitor design by the application based on the fitness function value determined for that candidate. At block 242 the method 230 may further comprise building the fractional order capacitor according to the selected fractional order capacitor design selected in block 240.

[0050] Turning now to FIG. 6, a method 260 is described. The method 260 may be used to design a fractional order capacitor (FOC) such as FOC 130 or FOC 150, as described above with reference to FIG. 2 and FIG. 3 respectively. At block 262, specify a frequency range for fractional order capacitor behavior. At block 264, specify a phase angle of fractional order capacitor behavior. At block 266, provide a list of dielectric materials and data on their permittivity. At block 268, an application executing on a computer selects a first and a second dielectric material from the list of dielectric materials based on the specified phase angle, based on the specified frequency range, based on the data on the permittivity of the first dielectric material, and based on the data on the permittivity of the second dielectric material. At block 270, the application determines a thickness of a composite dielectric layer of the fractional order capacitor design on determining a first thickness of the first dielectric material and a second thickness of the second dielectric material, where the thickness of the composite dielectric layer is based on the sum of the first and second thickness, where the first and second thicknesses are determined to achieve the specified phase angle of the fractional order capacitor over the specified frequency range of fractional order

behavior. At block 272, the application creates instructions for making the fractional order capacitor based on the selected dielectric materials, the first thickness, and the second thickness. In an embodiment the method further comprises, at block 274, building a fractional order capacitor according to the instructions for making the fractional order capacitor.

[0051] FIG. 7 illustrates a computer system 380 suitable for implementing one or more embodiments disclosed herein. The computer system 380 includes a processor 382 (which may be referred to as a central processor unit or CPU) that is in communication with memory devices including secondary storage 384, read only memory (ROM) 386, random access memory (RAM) 388, input/output (I/O) devices 390, and network connectivity devices 392. The processor 382 may be implemented as one or more CPU chips.

[0052] It is understood that by programming and/or loading executable instructions onto the computer system 380, at least one of the CPU 382, the RAM 388, and the ROM 386 are changed, transforming the computer system 380 in part into a particular machine or apparatus having the novel functionality taught by the present disclosure. It is fundamental to the electrical engineering and software engineering arts that functionality that can be implemented by loading executable software into a computer can be converted to a hardware implementation by well-known design rules. Decisions between implementing a concept in software versus hardware typically hinge on considerations of stability of the design and numbers of units to be produced rather than any issues involved in translating from the software domain to the hardware domain. Generally, a design that is still subject to frequent changes may be preferred to be implemented in software, because re-spinning a hardware implementation is more expensive than re-spinning a software design. Generally, a design that is stable that will be produced in large volume may be preferred to be implemented in hardware, for example in an application specific integrated circuit (ASIC), because for large production runs the hardware implementation may be less expensive than the software implementation. Often a design may be developed and tested in a software form and later transformed, by well-known design rules, to an equivalent hardware implementation in an application specific integrated circuit that hardwires the instructions of the software. In the same manner as a machine controlled by a new ASIC is a particular machine or apparatus, likewise a computer that has been

programmed and/or loaded with executable instructions may be viewed as a particular machine or apparatus.

[0053] Additionally, after the system 380 is turned on or booted, the CPU 382 may execute a computer program or application. For example, the CPU 382 may execute software or firmware stored in the ROM 386 or stored in the RAM 388. In some cases, on boot and/or when the application is initiated, the CPU 382 may copy the application or portions of the application from the secondary storage 384 to the RAM 388 or to memory space within the CPU 382 itself, and the CPU 382 may then execute instructions that the application is comprised of. In some cases, the CPU 382 may copy the application or portions of the application from memory accessed via the network connectivity devices 392 or via the I/O devices 390 to the RAM 388 or to memory space within the CPU 382, and the CPU 382 may then execute instructions that the application is comprised of. During execution, an application may load instructions into the CPU 382, for example load some of the instructions of the application into a cache of the CPU 382. In some contexts, an application that is executed may be said to configure the CPU 382 to do something, e.g., to configure the CPU 382 to perform the function or functions promoted by the subject application. When the CPU 382 is configured in this way by the application, the CPU 382 becomes a specific purpose computer or a specific purpose machine.

[0054] The secondary storage 384 is typically comprised of one or more disk drives or tape drives and is used for non-volatile storage of data and as an over-flow data storage device if RAM 388 is not large enough to hold all working data. Secondary storage 384 may be used to store programs which are loaded into RAM 388 when such programs are selected for execution. The ROM 386 is used to store instructions and perhaps data which are read during program execution. ROM 386 is a non-volatile memory device which typically has a small memory capacity relative to the larger memory capacity of secondary storage 384. The RAM 388 is used to store volatile data and perhaps to store instructions. Access to both ROM 386 and RAM 388 is typically faster than to secondary storage 384. The secondary storage 384, the RAM 388, and/or the ROM 386 may be referred to in some contexts as computer readable storage media and/or non-transitory computer readable media.

[0055] I/O devices 390 may include printers, video monitors, liquid crystal displays (LCDs), touch screen displays, keyboards, keypads, switches, dials, mice, track balls, voice recognizers, card readers, paper tape readers, or other well-known input devices.

[0056] The network connectivity devices 392 may take the form of modems, modem banks, Ethernet cards, universal serial bus (USB) interface cards, serial interfaces, token ring cards, fiber distributed data interface (FDDI) cards, wireless local area network (WLAN) cards, radio transceiver cards that promote radio communications using protocols such as code division multiple access (CDMA), global system for mobile communications (GSM), long-term evolution (LTE), worldwide interoperability for microwave access (WiMAX), near field communications (NFC), radio frequency identity (RFID), and/or other air interface protocol radio transceiver cards, and other well-known network devices. These network connectivity devices 392 may enable the processor 382 to communicate with the Internet or one or more intranets. With such a network connection, it is contemplated that the processor 382 might receive information from the network, or might output information to the network in the course of performing the above-described method steps. Such information, which is often represented as a sequence of instructions to be executed using processor 382, may be received from and outputted to the network, for example, in the form of a computer data signal embodied in a carrier wave.

[0057] Such information, which may include data or instructions to be executed using processor 382 for example, may be received from and outputted to the network, for example, in the form of a computer data baseband signal or signal embodied in a carrier wave. The baseband signal or signal embedded in the carrier wave, or other types of signals currently used or hereafter developed, may be generated according to several methods well-known to one skilled in the art. The baseband signal and/or signal embedded in the carrier wave may be referred to in some contexts as a transitory signal.

[0058] The processor 382 executes instructions, codes, computer programs, scripts which it accesses from hard disk, floppy disk, optical disk (these various disk based systems may all be considered secondary storage 384), flash drive, ROM 386, RAM 388, or the network connectivity devices 392. While only one processor 382 is shown, multiple processors may be present. Thus, while instructions may be discussed as executed by a processor, the instructions may be executed simultaneously, serially, or otherwise executed by one or multiple processors. Instructions, codes, computer programs, scripts, and/or data that may be accessed from the secondary storage 384, for example, hard drives, floppy disks, optical disks, and/or other device, the ROM 386,

and/or the RAM 388 may be referred to in some contexts as non-transitory instructions and/or non-transitory information.

[0059] In an embodiment, the computer system 380 may comprise two or more computers in communication with each other that collaborate to perform a task. For example, but not by way of limitation, an application may be partitioned in such a way as to permit concurrent and/or parallel processing of the instructions of the application. Alternatively, the data processed by the application may be partitioned in such a way as to permit concurrent and/or parallel processing of different portions of a data set by the two or more computers. In an embodiment, virtualization software may be employed by the computer system 380 to provide the functionality of a number of servers that is not directly bound to the number of computers in the computer system 380. For example, virtualization software may provide twenty virtual servers on four physical computers. In an embodiment, the functionality disclosed above may be provided by executing the application and/or applications in a cloud computing environment. Cloud computing may comprise providing computing services via a network connection using dynamically scalable computing resources. Cloud computing may be supported, at least in part, by virtualization software. A cloud computing environment may be established by an enterprise and/or may be hired on an as-needed basis from a third party provider. Some cloud computing environments may comprise cloud computing resources owned and operated by the enterprise as well as cloud computing resources hired and/or leased from a third party provider.

[0060] In an embodiment, some or all of the functionality disclosed above may be provided as a computer program product. The computer program product may comprise one or more computer readable storage medium having computer usable program code embodied therein to implement the functionality disclosed above. The computer program product may comprise data structures, executable instructions, and other computer usable program code. The computer program product may be embodied in removable computer storage media and/or non-removable computer storage media. The removable computer readable storage medium may comprise, without limitation, a paper tape, a magnetic tape, magnetic disk, an optical disk, a solid state memory chip, for example analog magnetic tape, compact disk read only memory (CD-ROM) disks, floppy disks, jump drives, digital cards, multimedia cards, and others. The computer program product may be suitable for loading, by the computer system 380, at least portions of the contents of the computer program product to the secondary

storage 384, to the ROM 386, to the RAM 388, and/or to other non-volatile memory and volatile memory of the computer system 380. The processor 382 may process the executable instructions and/or data structures in part by directly accessing the computer program product, for example by reading from a CD-ROM disk inserted into a disk drive peripheral of the computer system 380. Alternatively, the processor 382 may process the executable instructions and/or data structures by remotely accessing the computer program product, for example by downloading the executable instructions and/or data structures from a remote server through the network connectivity devices 392. The computer program product may comprise instructions that promote the loading and/or copying of data, data structures, files, and/or executable instructions to the secondary storage 384, to the ROM 386, to the RAM 388, and/or to other non-volatile memory and volatile memory of the computer system 380.

[0061] In some contexts, the secondary storage 384, the ROM 386, and the RAM 388 may be referred to as a non-transitory computer readable medium or a computer readable storage media. A dynamic RAM embodiment of the RAM 388, likewise, may be referred to as a non-transitory computer readable medium in that while the dynamic RAM receives electrical power and is operated in accordance with its design, for example during a period of time during which the computer system 380 is turned on and operational, the dynamic RAM stores information that is written to it. Similarly, the processor 382 may comprise an internal RAM, an internal ROM, a cache memory, and/or other internal non-transitory storage blocks, sections, or components that may be referred to in some contexts as non-transitory computer readable media or computer readable storage media.

[0062] Having described various devices and processes herein, specific aspects can include, but are not limited to:

[0063] In a first aspect, a fractional order capacitor, comprises: a first conductive plate connected to a first connecting terminal; a second conductive plate connected to a second connecting terminal; and a composite dielectric disposed between the first plate and the second plate, where the composite dielectric comprises a dielectric matrix material and filler particles, where the volume of the filler particles is less than 20% of the volume of the composite dielectric and where the filler particles comprise at least one material comprising a transition metal dichalcogenide.

[0064] A second aspect can include the fractional order capacitor of the first aspect, wherein the ratio of filler particles to dielectric matrix material is below a percolation threshold of the composite dielectric.

[0065] A third aspect can include the fractional order capacitor of any of the first to second aspects, wherein the filler particles comprise molybdenum disulfide (MoS_2), molybdenum ditelluride (MoTe_2), tungsten disulfide (WS_2), or tungsten diselenide (WSe_2).

[0066] A fourth aspect can include the fractional order capacitor of any of the first to third aspects, where the filler particles comprise a mix of particles having different dopant concentration levels.

[0067] A fifth aspect can include the fractional order capacitor of any of the first to fourth aspects, wherein the dielectric matrix material comprises hafnium dioxide (HfO_2), hafnium silicate (HfSiO_4), zirconium dioxide (ZrO_2), or zirconium silicate (ZrSiO_4).

[0068] A sixth aspect can include the fractional order capacitor of any of the first to fifth aspects, wherein the dielectric matrix material comprises a polymer material.

[0069] In a seventh aspect, a method of making a fractional order capacitor (FOC), comprising: specifying a frequency range for fractional order capacitor behavior; specifying a phase angle of fractional order capacitor behavior; providing a list of filler materials and data on their permittivity and conductivity; providing a list of dielectric matrix materials and data on their permittivity; determining a fitness function value for each of a plurality of different candidate fractional order capacitor designs by an application executing on a computer, where each design defines a fill fraction for filler materials, identifies a filler material, and identifies a dielectric matrix material and where the fitness function value is determined based on evaluating the phase angle of the candidate design at each of a plurality of frequencies within the specified frequency range for fractional order capacitor behavior; obtaining different candidate fractional order capacitor designs by the application in part using a genetic algorithm and based on the fitness function value of some candidate fractional order capacitor designs; selecting a candidate fractional order capacitor design by the application based on the fitness function value determined for that candidate; creating instructions for making a composite dielectric composed of the dielectric matrix material and the filler material based on the selected candidate fractional order capacitor design; and manufacturing a fractional order capacitor based at least in part on the instructions for making the composite dielectric.

[0070] An eighth aspect can include the method of the seventh aspect, wherein the list of filler materials comprises transition metal dichalcogenide semiconductor materials.

[0071] A ninth aspect can include the method of the eighth aspect, wherein the transition metal dichalcogenide semiconductor materials comprise molybdenum disulfide (MoS_2), molybdenum ditelluride (MoTe_2), tungsten disulfide (WS_2), or tungsten diselenide (WSe_2).

[0072] A tenth aspect can include the method of any of the seventh to ninth aspects, wherein the list of filler materials comprises single walled carbon nanotubes.

[0073] An eleventh aspect can include the method of any of the seventh to tenth aspects, wherein the list of dielectric matrix materials comprises high-k dielectric materials.

[0074] A twelfth aspect can include the method of the eleventh aspect, wherein the high-k dielectric materials comprise hafnium dioxide (HfO_2), hafnium silicate (HfSiO_4), zirconium dioxide (ZrO_2), and zirconium silicate (ZrSiO_4).

[0075] A thirteenth aspect can include the method of any of the seventh to twelfth aspects, wherein the fitness function value is determined as a sum of squares of differences between the phase angle of fractional order capacitor behavior that is specified and a phase angle of the candidate design at each of the plurality of frequencies.

[0076] A fourteenth aspect can include the method of any of the seventh to thirteenth aspects, wherein the phase angle of the candidate design is evaluated at each of the plurality of frequencies based on an effective permittivity of a composite dielectric composed of the dielectric matrix and the filler material, where the effective permittivity of the composite dielectric is determined based on an effective medium approximation model.

[0077] A fifteenth aspect can include the method of the fourteenth aspect, wherein the effective medium approximation model is based on a multiphase Maxwell-Garnett mixing rule.

[0078] In a sixteenth aspect, a method of determining a design for a fractional order capacitor (FOC), comprises: providing a list of filler materials and data on their permittivity and conductivity, where the list comprises molybdenum disulfide (MoS_2), molybdenum ditelluride (MoTe_2), tungsten disulfide (WS_2), tungsten diselenide (WSe_2), and single walled carbon nanotubes; providing a list of dielectric matrix materials and

data on their permittivity, where the list comprises hafnium dioxide (HfO_2), hafnium silicate (HfSiO_4), zirconium dioxide (ZrO_2), and zirconium silicate (ZrSiO_4); determining a fitness function value for each of a plurality of different candidate fractional order capacitor designs by an application executing on a computer, where each design defines a fill fraction for filler materials, identifies a filler material, and identifies a dielectric matrix material and where the fitness function value is determined based on determining the phase angle of the candidate design at each of a plurality of frequencies within a predefined frequency range for fractional order capacitor behavior using a model for dielectric mixtures and comparing to a target phase angle; obtaining different candidate fractional order capacitor designs by the application in part using a genetic algorithm and based on the fitness function value of some candidate fractional order capacitor designs; and selecting a candidate fractional order capacitor design by the application based on the fitness function value determined for that candidate.

[0079] A seventeenth aspect can include the method of the sixteenth aspect, further comprising creating instructions for making a composite dielectric composed of the dielectric matrix material and the filler material based on the selected candidate fractional order capacitor design.

[0080] A eighteenth aspect can include the method of the seventeenth aspect, further comprising manufacturing a fractional order capacitor based at least in part on the instructions for making the composite dielectric.

[0081] A nineteenth aspect can include the method of the sixteenth aspect, wherein at least some of the designs designate a dopant concentration level for a filler material.

[0082] A twentieth aspect can include the method of the sixteenth aspect, wherein determining the phase angle of the candidate design at each of a plurality of frequencies is based on an effective medium approximation model.

[0083] A twenty first aspect can include the method of the twentieth aspect, wherein the effective medium approximation model is a multiphase Maxwell-Garnett mixing rule.

[0084] In a twenty second aspect, a method of determining a design for a fractional order capacitor (FOC), comprises: specifying a frequency range for fractional order capacitor behavior; specifying a phase angle of fractional order capacitor behavior; providing a list of dielectric materials and data on their permittivity; selecting a first and a second dielectric material from the list of dielectric materials by an application executing on a computer system based on the specified phase angle, based on the specified frequency range, based on the data on the permittivity of the first dielectric material, and

based on the data on the permittivity of the second dielectric material; determining a thickness of a composite dielectric layer of the fractional order capacitor design by the application based on determining a first thickness of the first dielectric material and a second thickness of the second dielectric material, where the thickness of the composite dielectric layer is based on the sum of the first and second thickness, where the first and second thicknesses are determined to achieve the specified phase angle of the fractional order capacitor over the specified frequency range of fractional order behavior; and creating instructions for making the fractional order capacitor by the application based on the selected dielectric materials, the first thickness, and the second thickness.

[0085] A twenty third aspect can include the method of the twenty second aspect, further comprising: selecting a third dielectric material from the list of dielectric materials by the application based on the specified phase angle, based on the specified frequency range, and based on the data on the permittivity of the third dielectric material; and determining the thickness of the composite dielectric layer of the fractional order capacitor design by the application further based on determining a third thickness of the third dielectric material, where the thickness of the composite dielectric layer is determined based on the sum of the first, second, and third thickness, where the first, second, and third thicknesses are determined to achieve the specified phase angle of the fractional order capacitor over the specified frequency range of fractional order behavior.

[0086] A twenty fourth aspect can include the method of the twenty second to twenty third aspects, wherein providing the list of dielectric materials and data on their permittivity is accomplished by embedding the list and data in the application or by the application reading the list and data from a configuration file stored on the computer.

[0087] While several embodiments have been provided in the present disclosure, it should be understood that the disclosed systems and methods may be embodied in many other specific forms without departing from the spirit or scope of the present disclosure. The present examples are to be considered as illustrative and not restrictive, and the intention is not to be limited to the details given herein. For example, the various elements or components may be combined or integrated into another system or certain features may be omitted or not implemented.

[0088] Also, techniques, systems, subsystems, and methods described and illustrated in the various embodiments as discrete or separate may be combined or

integrated with other systems, modules, techniques, or methods without departing from the scope of the present disclosure. Other items shown or discussed as directly coupled or communicating with each other may be indirectly coupled or communicating through some interface, device, or intermediate component, whether electrically, mechanically, or otherwise. Other examples of changes, substitutions, and alterations are ascertainable by one skilled in the art and could be made without departing from the spirit and scope disclosed herein.

CLAIMS

What is claimed is:

1. A fractional order capacitor, comprising:
 - a first conductive plate connected to a first connecting terminal;
 - a second conductive plate connected to a second connecting terminal; and
 - a composite dielectric disposed between the first plate and the second plate, where the composite dielectric comprises a dielectric matrix material and filler particles, where the volume of the filler particles is less than 20% of the volume of the composite dielectric and where the filler particles comprise at least one material comprising a transition metal dichalcogenide.
2. The fractional order capacitor of claim 1, wherein the ratio of filler particles to dielectric matrix material is below a percolation threshold of the composite dielectric.
3. The fractional order capacitor of claim 1, wherein the filler particles comprise molybdenum disulfide (MoS_2), molybdenum ditelluride (MoTe_2), tungsten disulfide (WS_2), or tungsten diselenide (WSe_2).
4. The fractional order capacitor of claim 1, where the filler particles comprise a mix of particles having different dopant concentration levels.
5. The fractional order capacitor of claim 1, wherein the dielectric matrix material comprises hafnium dioxide (HfO_2), hafnium silicate (HfSiO_4), zirconium dioxide (ZrO_2), or zirconium silicate (ZrSiO_4).
6. The fractional order capacitor of claim 1, wherein the dielectric matrix material comprises a polymer material.
7. A method of making a fractional order capacitor (FOC), comprising:
 - specifying a frequency range for fractional order capacitor behavior;
 - specifying a phase angle of fractional order capacitor behavior;
 - providing a list of filler materials and data on their permittivity and conductivity;
 - providing a list of dielectric matrix materials and data on their permittivity;
 - determining a fitness function value for each of a plurality of different candidate fractional order capacitor designs by an application executing on a computer, where each design defines a fill fraction for filler materials, identifies a filler material, and identifies a dielectric matrix material and where the fitness function value is determined based on evaluating the phase angle of the candidate design at each of a plurality of frequencies

- within the specified frequency range for fractional order capacitor behavior;
- obtaining different candidate fractional order capacitor designs by the application in part using a genetic algorithm and based on the fitness function value of some candidate fractional order capacitor designs;
- selecting a candidate fractional order capacitor design by the application based on the fitness function value determined for that candidate;
- creating instructions for making a composite dielectric composed of the dielectric matrix material and the filler material based on the selected candidate fractional order capacitor design; and
- manufacturing a fractional order capacitor based at least in part on the instructions for making the composite dielectric.
8. The method of claim 7, wherein the list of filler materials comprises transition metal dichalcogenide semiconductor materials.
 9. The method of claim 8, wherein the transition metal dichalcogenide semiconductor materials comprise molybdenum disulfide (MoS_2), molybdenum ditelluride (MoTe_2), tungsten disulfide (WS_2), or tungsten diselenide (WSe_2).
 10. The method of claim 7, wherein the list of filler materials comprises single walled carbon nanotubes.
 11. The method of claim 7, wherein the list of dielectric matrix materials comprises high-k dielectric materials.
 12. The method of claim 11, wherein the high-k dielectric materials comprise hafnium dioxide (HfO_2), hafnium silicate (HfSiO_4), zirconium dioxide (ZrO_2), and zirconium silicate (ZrSiO_4).
 13. The method of claim 7, wherein the fitness function value is determined as a sum of squares of differences between the phase angle of fractional order capacitor behavior that is specified and a phase angle of the candidate design at each of the plurality of frequencies.
 14. The method of claim 7, wherein the phase angle of the candidate design is evaluated at each of the plurality of frequencies based on an effective permittivity of a composite dielectric composed of the dielectric matrix and the filler material, where the effective permittivity of the composite dielectric is determined based on an effective medium approximation model.

15. The method of claim 14, wherein the effective medium approximation model is based on a multiphase Maxwell-Garnett mixing rule.
16. A method of determining a design for a fractional order capacitor (FOC), comprising:
- providing a list of filler materials and data on their permittivity and conductivity, where the list comprises molybdenum disulfide (MoS_2), molybdenum ditelluride (MoTe_2), tungsten disulfide (WS_2), tungsten diselenide (WSe_2), and single walled carbon nanotubes;
 - providing a list of dielectric matrix materials and data on their permittivity, where the list comprises hafnium dioxide (HfO_2), hafnium silicate (HfSiO_4), zirconium dioxide (ZrO_2), and zirconium silicate (ZrSiO_4);
 - determining a fitness function value for each of a plurality of different candidate fractional order capacitor designs by an application executing on a computer, where each design defines a fill fraction for filler materials, identifies a filler material, and identifies a dielectric matrix material and where the fitness function value is determined based on determining the phase angle of the candidate design at each of a plurality of frequencies within a predefined frequency range for fractional order capacitor behavior using a model for dielectric mixtures and comparing to a target phase angle;
 - obtaining different candidate fractional order capacitor designs by the application in part using a genetic algorithm and based on the fitness function value of some candidate fractional order capacitor designs; and
 - selecting a candidate fractional order capacitor design by the application based on the fitness function value determined for that candidate.
17. The method of claim 16, further comprising creating instructions for making a composite dielectric composed of the dielectric matrix material and the filler material based on the selected candidate fractional order capacitor design.
18. The method of claim 17, further comprising manufacturing a fractional order capacitor based at least in part on the instructions for making the composite dielectric.
19. The method of claim 16, wherein at least some of the designs designate a dopant concentration level for a filler material.

20. The method of claim 16, wherein determining the phase angle of the candidate design at each of a plurality of frequencies is based on an effective medium approximation model.
21. The method of claim 20, wherein the effective medium approximation model is a multiphase Maxwell-Garnett mixing rule.
22. A method of determining a design for a fractional order capacitor (FOC), comprising:
- specifying a frequency range for fractional order capacitor behavior;
 - specifying a phase angle of fractional order capacitor behavior;
 - providing a list of dielectric materials and data on their permittivity;
 - selecting a first and a second dielectric material from the list of dielectric materials by an application executing on a computer system based on the specified phase angle, based on the specified frequency range, based on the data on the permittivity of the first dielectric material, and based on the data on the permittivity of the second dielectric material;
 - determining a thickness of a composite dielectric layer of the fractional order capacitor design by the application based on determining a first thickness of the first dielectric material and a second thickness of the second dielectric material, where the thickness of the composite dielectric layer is based on the sum of the first and second thickness, where the first and second thicknesses are determined to achieve the specified phase angle of the fractional order capacitor over the specified frequency range of fractional order behavior; and
 - creating instructions for making the fractional order capacitor by the application based on the selected dielectric materials, the first thickness, and the second thickness.
23. The method of claim 22, further comprising:
- selecting a third dielectric material from the list of dielectric materials by the application based on the specified phase angle, based on the specified frequency range, and based on the data on the permittivity of the third dielectric material; and
 - determining the thickness of the composite dielectric layer of the fractional order capacitor design by the application further based on determining a third thickness of the third dielectric material, where the thickness of the

composite dielectric layer is determined based on the sum of the first, second, and third thickness, where the first, second, and third thicknesses are determined to achieve the specified phase angle of the fractional order capacitor over the specified frequency range of fractional order behavior.

24. The method of claim 22, wherein providing the list of dielectric materials and data on their permittivity is accomplished by embedding the list and data in the application or by the application reading the list and data from a configuration file stored on the computer.

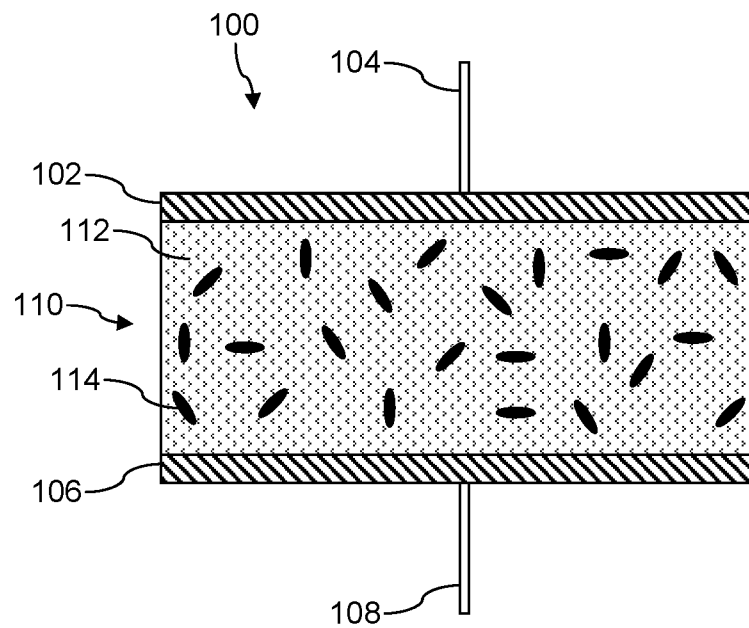


FIG. 1

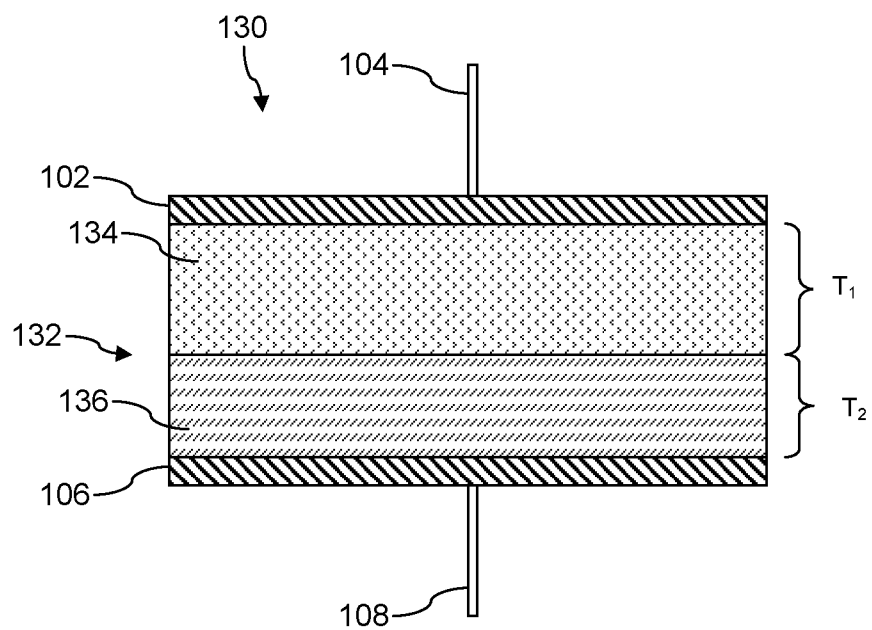


FIG. 2

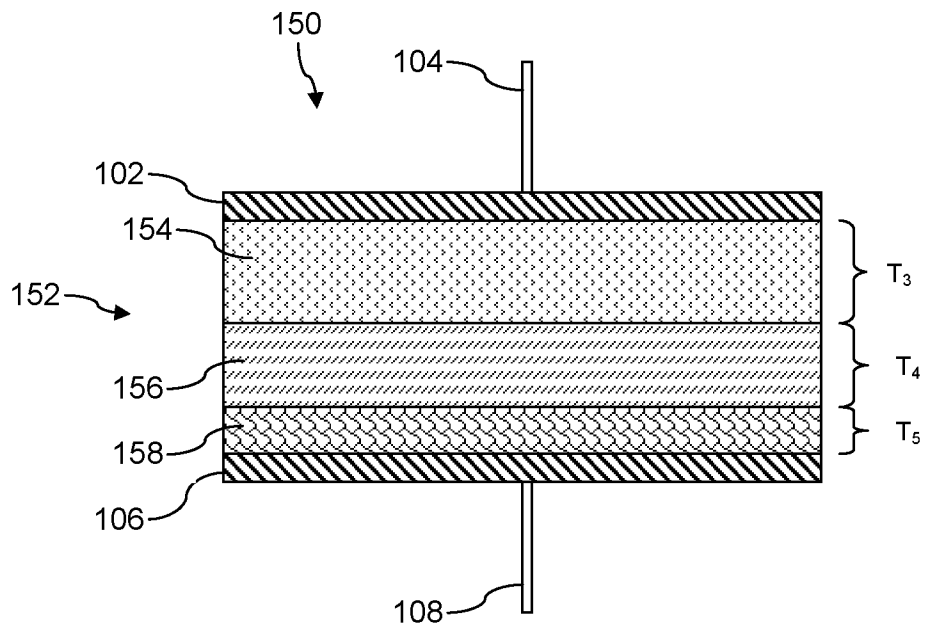


FIG. 3

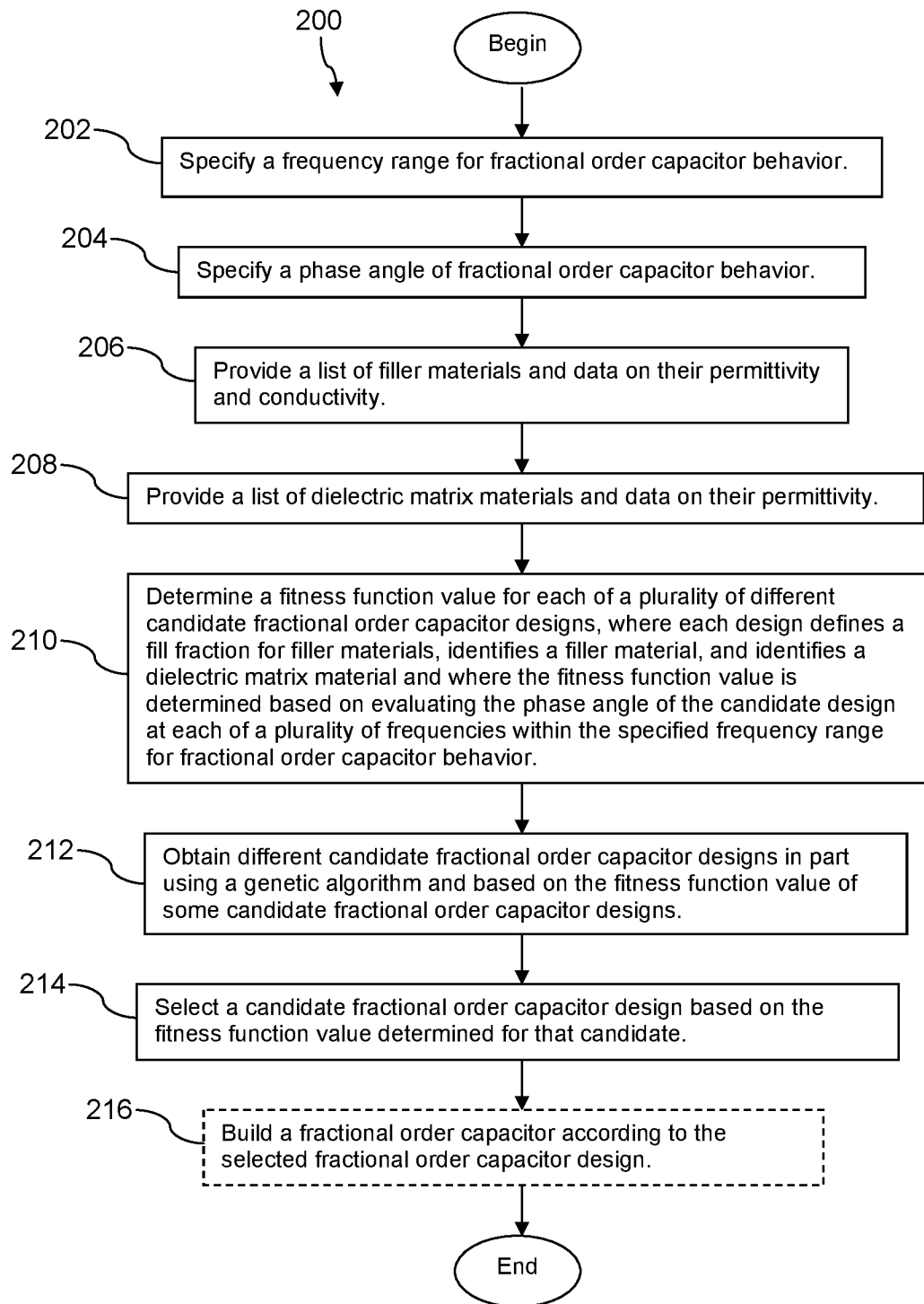


FIG. 4

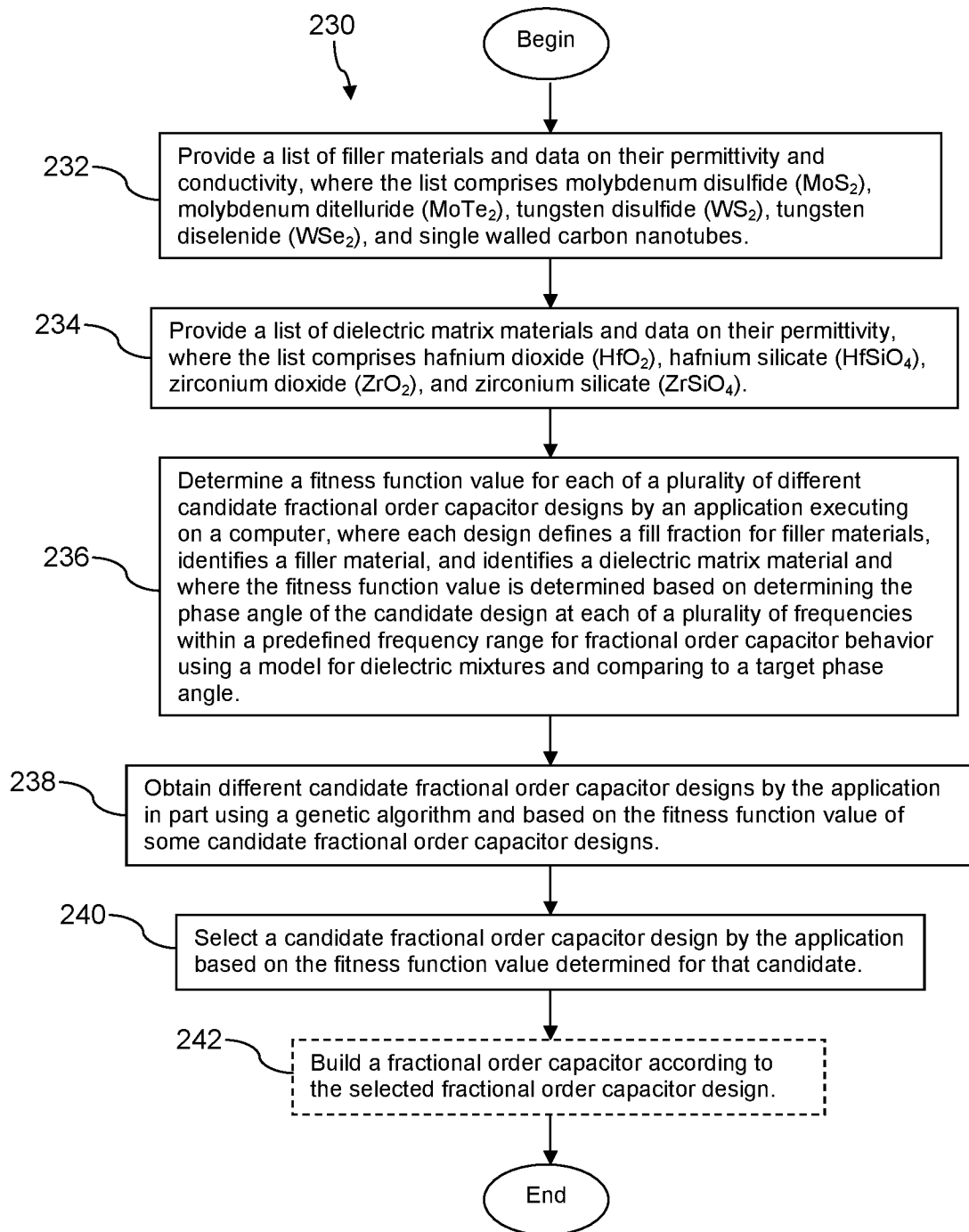


FIG. 5

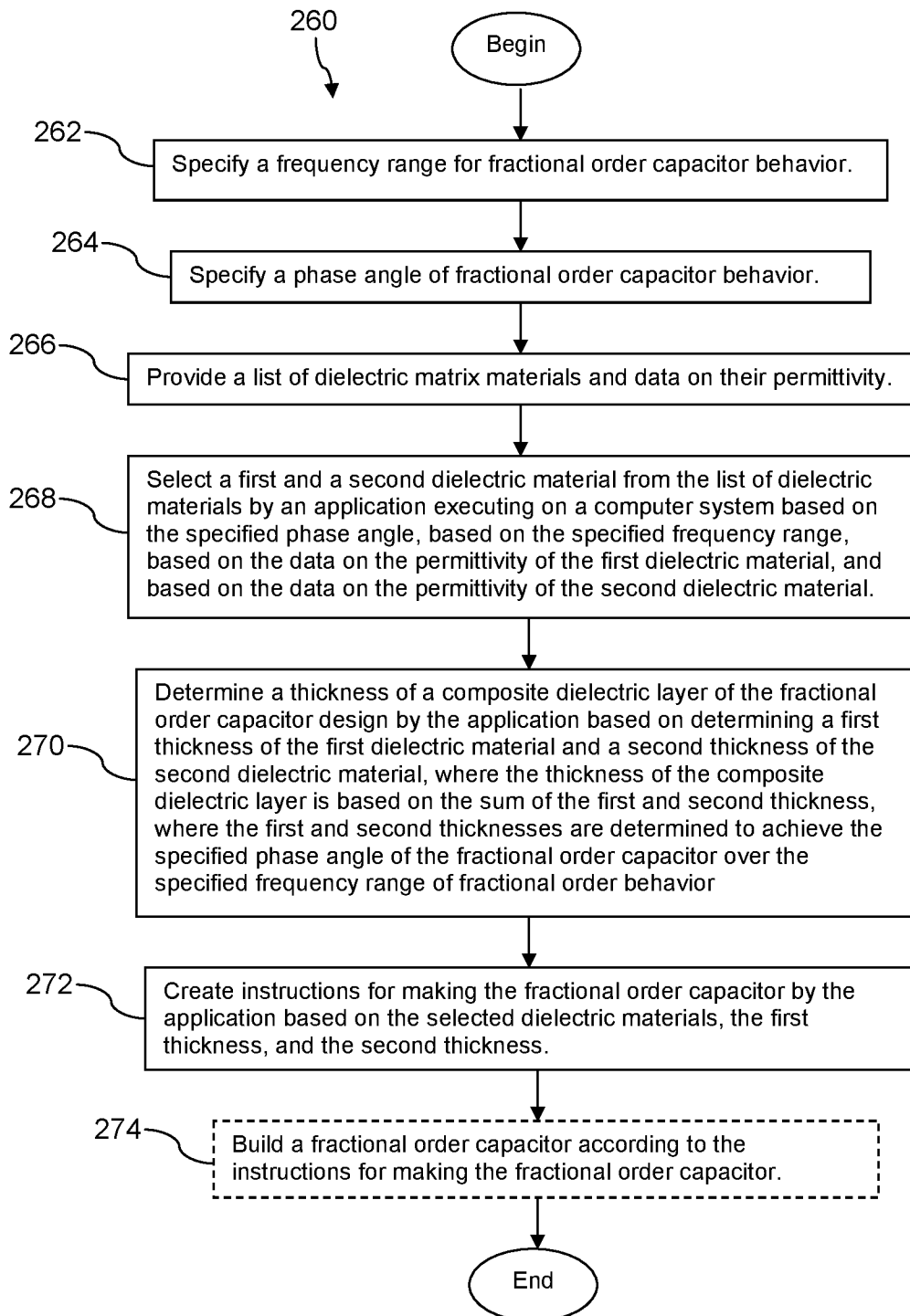


FIG. 6

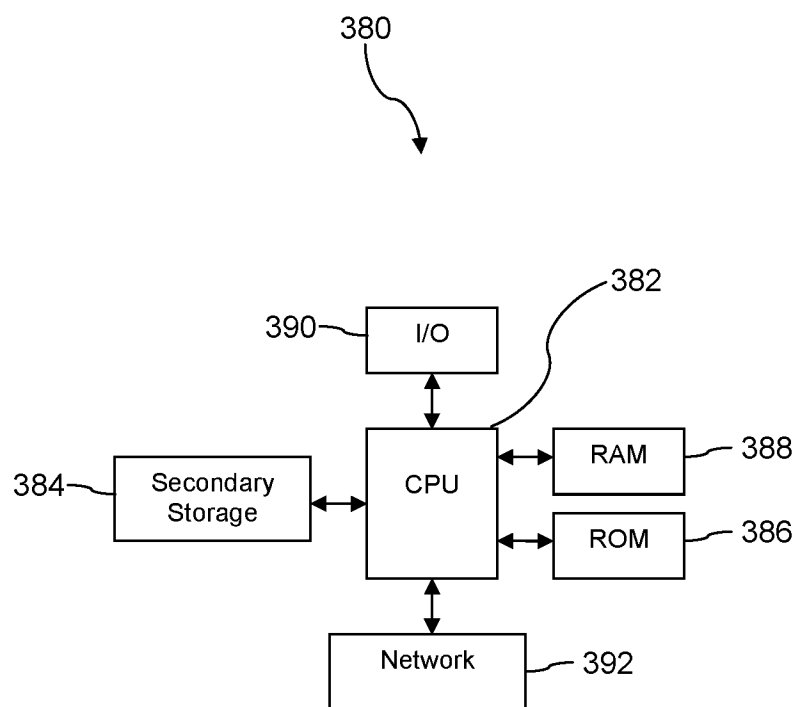


FIG. 7

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2018/052736

A. CLASSIFICATION OF SUBJECT MATTER INV. H01G4/12 H01G4/20 ADD.		
According to International Patent Classification (IPC) or to both national classification and IPC		
B. FIELDS SEARCHED Minimum documentation searched (classification system followed by classification symbols) H01G G06N		
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched		
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) EPO-Internal		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	QINGCHAO JIA ET AL: "MoS2 Nanosheet Superstructures Based Polymer Composites for High-Dielectric and Electrical Energy Storage Applications", JOURNAL OF PHYSICAL CHEMISTRY C, vol. 120, no. 19, 2 May 2016 (2016-05-02), pages 10206-10214, XP055501572, ISSN: 1932-7447, DOI: 10.1021/acs.jpcc.6b02968	1-4,6-9, 13-15
A	page 10206, right-hand column, last paragraph - page 10207, left-hand column, paragraph 1 page 10207, right-hand column, paragraph 2 page 10209, left-hand column, paragraph 2; figures 5, S4 -/--	5,11,12
☒ Further documents are listed in the continuation of Box C. ☒ See patent family annex.		
* Special categories of cited documents :		
"A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier application or patent but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family	
Date of the actual completion of the international search 29 August 2018	Date of mailing of the international search report 06/09/2018	
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Pantelidis, D	

INTERNATIONAL SEARCH REPORT

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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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