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(54) **RESONATOR**

(57) Aresonator and method are disclosed. The resonator comprises: a resonant chamber defined by a first wall, a second wall opposing said first wall and side walls extending between said first wall and said second wall; and a plurality of concentric tubular structures, each tubular structure being formed by a first resonant element and a second resonant element separated by an intra-structure gap and located in proximity with each other for magnetic field coupling between said first resonant element and said second resonant element, said first resonant element being grounded on said first wall and extending into said resonant chamber from said first wall, said second resonant element being grounded on said second wall and extending into said resonant chamber from said second wall, each tubular structure being separated by an interstructure gap and located in proximity with each other for magnetic field coupling between first and second resonant elements of adjacent tubular structures. In this way, coupling is provided not only between the resonant elements making up each tubular structure, but also between resonant elements of different tubular structure which provides for an even greater level of miniaturisation compared to previous approaches, while still retaining the same degree of performance as existing resonators.

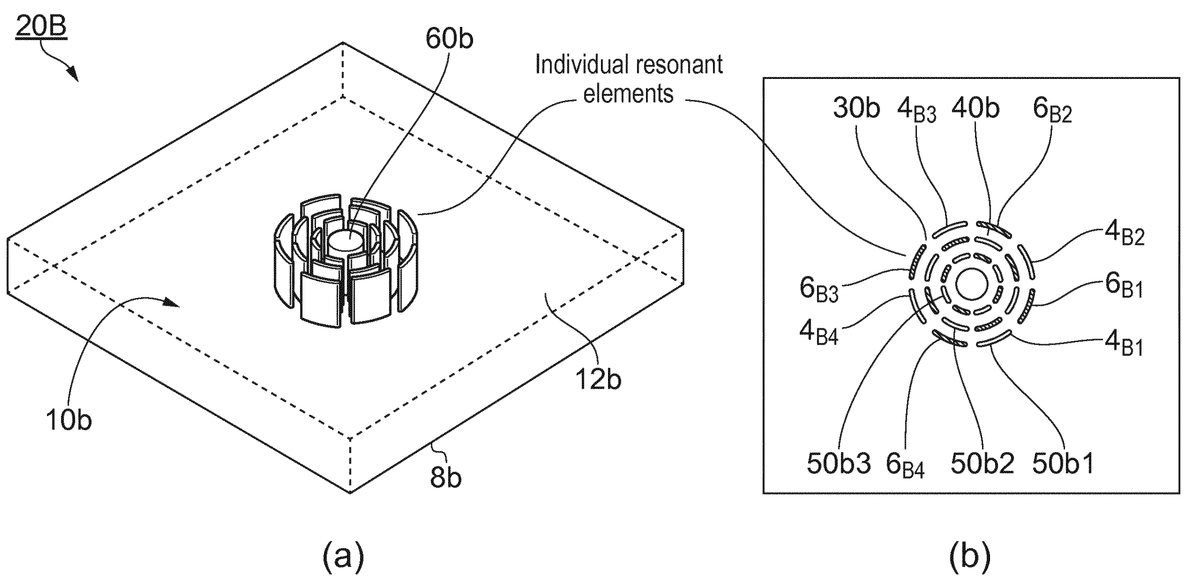

FIG. 5

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Description

FIELD OF THE INVENTION

[0001] The present invention relates to a resonator for telecommunications. Embodiments relate to a resonator assembly for radio frequency (RF) filters and a method.

BACKGROUND

[0002] Filters are widely used in telecommunications. Their applications vary from mobile cellular base stations, through radar systems, amplifier linearization, to point-to-point radio and RF signal cancellation, to name a few. The choice of a filter is ultimately dependent on the application; however, there are certain desirable characteristics that are common to all filter realisations. For example, the amount of insertion loss in the pass-band of the filter should be as low as possible, while the attenuation in the stop-band should be as high as possible. Further, in some applications, the guard band - the frequency separation between the pass-band and stop-band - needs to be very small, which requires filters of high-order to be deployed in order to achieve this requirement. However, the requirement for a high-order filter is always accompanied by an increase in the cost (due to a greater number of components that a filter requires) and size. Furthermore, even though increasing the order of the filter increases the attenuation in the stop-band, this inevitably increases the losses in the pass-band.

[0003] One of the challenging tasks in filter design is filter size reduction with a simultaneous retention of excellent electrical performance comparable with larger structures. One of the main parameters governing filter's selectivity and insertion loss is the so-called quality factor of the elements comprising the filter - "Q factor". The Q factor is defined as the ratio of energy stored in the element to the time-averaged power loss. For lumped elements that are used particularly at low RF frequencies for filter design, Q is typically in the range of ~ 60-100 whereas, for cavity type resonators, Q can be as high as several 1000s. Although lumped components offer significant miniaturization, their low Q factor prohibits their use in highly-demanding applications where high rejection and/or selectivity is required. On the other hand, cavity resonators offer sufficient Q, but their size prevents their use in many applications. The miniaturization problem is particularly pressing with the advent of small cells, where the volume of the base station should be minimal, since it is important the base station be as inconspicuous as possible (as opposed to an eyesore). Moreover, the currently-observed trend of macrocell base stations lies with multiband solutions within a similar mechanical envelope to that of single-band solutions without sacrificing the system's performance. Accordingly, it is desired to minimize the physical size and profile of cavity resonators/filters (that can offer the high Q), focusing on a low-profile suitable also for small-cell outdoor products.

SUMMARY

[0004] According to a first aspect, there is provided a resonator, comprising: a resonant chamber defined by a first wall, a second wall opposing the first wall and side walls extending between the first wall and the second wall; and a plurality of concentric tubular structures, each tubular structure being formed by a first resonant element and a second resonant element separated by an intra-structure gap and located in proximity with each other for magnetic field coupling between the first resonant element and the second resonant element, the first resonant element being grounded on the first wall and extending into the resonant chamber from the first wall, the second resonant element being grounded on the second wall and extending into the resonant chamber from the second wall, each tubular structure being separated by an inter-structure gap and located in proximity with each other for magnetic field coupling between first and second resonant elements of adjacent tubular structures.

[0005] The first aspect recognises that solutions exist which fail to provide suitable performance with a minimal size profile. For lower-performance requirements, ceramic mono-block filters with external metallization are typically used. They offer significant size reduction but with relatively low Q of a few 100's (up to 500), which is too low for many applications. Additionally, the small size of the filters prevents their use in high-power applications, due to relatively high insertion losses and rather limited power-handling capabilities. Ceramic resonators, like mono-block filters, also offer significant size reductions. Furthermore, the filters offer power-handling capabilities that are much higher than those of mono-block filters. However, the cost is the main prohibiting factor for wider deployment of these filters. Cavity filters are suited to high-power applications, but they are relatively large, which is the principal limiting factor for their widespread use. Size reduction of traditional combline resonators is achieved by employing capacitive caps to increase the diameter of the resonator's top end so as to provide a greater electric loading and hence reduce the frequency of operation. However, this approach needs to be taken with care, since it reduces the Q factor. A distributed resonator which utilises a so-called folded arrangement of 9 individual resonator elements, where each element is a standard coaxial, 90 degree long resonator post results in a tremendous size reduction with an added benefit - frequency agility. However, the main disadvantage of the distributed resonator lies with the choice of the individual resonator elements - simple coaxial resonator elements in this case. The first aspect also recognises that the resultant size reduction is, ultimately, a function of its resonator elements.

[0006] Accordingly, a resonator, resonant device or filer may be provided. The resonator may comprise a resonant chamber or cavity. The chamber may be defined or have a first wall and a second wall opposing or facing the first wall. The chamber may have side walls which extend between or join the first wall and the second wall. The resonator may also comprise a plurality of structures. The structures may be tubular or hollow. The structures may be concentric or coaxially located. Each tubular structure may be formed of resonant elements. The resonant elements forming the structure may be separated by an intra-structure gap. In other words, the structures may be formed from discreet resonant elements, each separated by the intra-structure gap. The resonant elements may be located in proximity with each other to provide magnetic field coupling between them. One of the resonant elements may be grounded on the first wall and may extend, upstand or depend from that wall into the resonant chamber. Another resonant element may be grounded on the second wall and may extend, upstand or depend from that wall into the resonant chamber. Each of the tubular structures may be separated by an inter-structure gap between them. Each of the tubular structures may be located in proximity with each other to provide magnetic field coupling between resonant elements of adjacent tubular structures. In this way, coupling is provided not only between the resonant elements making up each tubular structure, but also between resonant elements of different tubular structure which provides for an even greater level of miniaturisation compared to previous approaches, while still retaining the same degree of performance as existing resonators.

[0007] In one embodiment, the first resonant element and the second resonant elements comprise a pair of resonant elements and each tubular structure comprises a plurality of pairs of resonant elements. Accordingly, the first and second resonant elements may be provided as pairs of resonant elements. Each tubular structure may comprise one or more pairs of such resonant elements. Accordingly, each tubular structure may comprise an even number of resonant elements.

[0008] In one embodiment, each tubular structure may comprise the same number of resonant elements.

[0009] In one embodiment, the plurality of pairs of resonant elements extend circumferentially around the tubular structure. Accordingly, the resonant elements may extend, be located or positioned circumferentially to define the tubular structure.

[0010] In one embodiment, the first resonant elements and the second resonant elements alternate circumferentially around the tubular structure. Accordingly, the first and second resonant elements may be alternately located or positioned circumferentially around the tubular structure. This provides an inter-digitated arrangement where each first resonant element neighbours or is adjacent typically to second resonant elements, one on either side of the first resonant element within the tubular structure, and vice-versa.

[0011] In one embodiment, the first and the second resonant elements define constant intra-structure gaps. Accordingly, the distance between each resonant element within the tubular structure may be the same, constant, identical or matching.

[0012] In one embodiment, the first and the second resonant elements are symmetric about their intra-structure gap.

[0013] In one embodiment, the first and the second resonant elements present one of opposing parallel and divergent faces.

[0014] In one embodiment, the first and the second resonant elements have one of a polygonal and curved cross-sectional area. Accordingly, the resonant elements may have a variety of different cross-sectional areas which suit magnetic field coupling therebetween. For example, the resonant elements may have a polygonal configuration or may have a curved configuration such as circular, elliptical, annular or a portion or arc thereof.

[0015] In one embodiment, the first and the second resonant elements are elongate.

[0016] In one embodiment, the first and second resonant elements define cylindrical sectors or segments extending along a central axis. Accordingly, the resonant elements defining the cylindrical sections may have an annular arc cross-section.

[0017] In one embodiment, the plurality of concentric tubular structures are radially displaced with respect to each other. Accordingly, the tubular structures may be concentric or coaxial. In other words, the tubular structures may be nested with an inner of the tubular structures being surrounded by an outer of the tubular structures.

[0018] In one embodiment, the first and the second resonant elements of adjacent tubular structures alternate radially, each separated by the inter-structure gap. Accordingly, resonant elements of adjacent tubular structures may alternate radially between first and second resonant elements. This helps to ensure that first and second resonant elements are adjacent each other to provide for magnetic field coupling between concentric tubular structures.

[0019] In one embodiment, the first and second resonant elements of adjacent tubular structures define constant inter-structure gaps. Accordingly, the distance between each resonant element between different tubular structures maybe the same, constant, identical or matching.

[0020] In one embodiment, intra-structure gaps of adjacent tubular structures are radially aligned.

[0021] In one embodiment, the resonator comprises a tuning screw concentrically located within an innermost tubular structure. The tuning screw may also be a resonator element.

[0022] In one embodiment, the resonator comprises an incoming signal feed coupled with one of the first and the second resonant elements and an outgoing signal feed coupled with another of the first and the second resonant elements.

[0023] According to a second aspect, there is provided a method of radio frequency filtering, comprising passing a signal for filtering through at least one resonator of the first aspect.

[0024] Further particular and preferred aspects are set out in the accompanying independent and dependent claims. Features of the dependent claims may be combined with features of the independent claims as appropriate, and in combinations other than those explicitly set out in the claims.

[0025] Where an apparatus feature is described as being operable to provide a function, it will be appreciated that this includes an apparatus feature which provides that function or which is adapted or configured to provide that function.

BRIEF DESCRIPTION OF THE DRAWINGS

[0026] Embodiments of the present invention will now be described further, with reference to the accompanying drawings, in which:

Figure 1 illustrates a component building-block structure of a resonator;
F lustrates an equivalent circuit of the resonator shown in Figure 1;
F s a graph of frequency variation as a function of transformer impedance, $Z_t = \frac{1}{Y_t}$ according to equation (5) below for the resonator structure shown in Figure 1;
Figure 4 illustrates an arrangement of an existing mini-coax resonator; (a) is an isometric view and (b) is a top view;
Figure 5 illustrates a distributed resonator with 25 individual resonator elements according to one embodiment; (a) is an isometric view and (b) is a top view;
Figure 6 illustrates a distributed resonator with 17 individual resonator elements according to one embodiment; (a) is an isometric view and (b) is a top view; and
Figure 7 illustrates a distributed resonator with 25 individual resonator elements according to one embodiment; (a) is an isometric view and (b) is a top view.

DESCRIPTION OF THE EMBODIMENTS

[0027] Before discussing the embodiments in any more detail, first an overview will be provided. Embodiments provide a resonator, resonant structure or filter which provides for high Q whilst minimizing the physical size of the resonator. This is achieved by providing split resonant pairs arranged to form one or more inter-digitated slotted tubes. The inter-digitated slotted tubes are coaxially or concentrically located and positioned so one tubular structure surrounds another. Each pair of resonators achieves strong coupling, not only between adjacent resonant elements within each tubular structure, but also between adjacent resonant elements of adjacent tubular structures. The coupling between adjacent pairs exists in multiple directions, which provides for additional paths which provides for even greater miniaturization. Different layouts are possible to form each tubular structure, which need not be cylindrical. Typically, an intra-structure gap exists between each resonant element within a tubular structure. Although the intra-structure gap is typically the same for each resonant element within the tubular structure, the gap can also be varied depending on design requirements in order to adjust magnetic coupling between resonant elements. Typically, each tubular structure is separated by an inter-structure gap. Although the inter-structure gap is typically the same between each tubular structure, this can also be varied, depending on design requirements, in order to vary the magnetic coupling between resonant elements of different tubular structures. Typically, the resonant elements present opposed non-planar surfaces separated by the intra-structure gap, although planar configurations are also envisaged. Where a gap is defined by opposing planar surfaces then the gap may be considered to be defined as a constant width between the adjacent resonator elements defined by the profile of those opposing planar surfaces. Where a gap is defined by opposing non-planar surfaces then the gap may be considered to be defined as a varying width between the adjacent resonant elements defined by the profile of those opposing non-planar surfaces. Typically, the resonant elements present opposed non-planar surfaces separated by the inter-structure gap, although planar configurations are also envisaged. Where a gap is defined by opposing complimentary non-planar surfaces then the gap may be considered to be defined as a constant width between the adjacent resonator elements defined by the profile of those opposing non-planar surfaces. Where a gap is defined by opposing planar or non-complimentary surfaces then the gap may be considered to be defined as a varying width between the adjacent resonant elements defined by the profile of those opposing planar or non-complimentary surfaces. Although the resonant elements of adjacent tubular structures are located to completely align radially with maximum overlap (in other words, the intra-structure gap of each tubular structure aligns radially), it will be appreciated that this need not be the case and that adjacent resonant elements from adjacent tubular structures maybe circumferentially offset, depending on design requirements, in order to vary the magnetic coupling between tubular structures. This provides for an even greater level of miniaturisation compared to previous approaches, while still retaining the same degree of performance as existing resonators.

[0028] Figure 1 illustrates a layout of an existing resonator structure 2 in which there are two resonator posts 4, 6, one

4 of which is grounded on the bottom 8 of a resonator cavity 10 and the other 6 of which is grounded on the top 12 of the resonator cavity 10. This general resonant structure 2 is a building-block of resonator structures of embodiments.

[0029] It will be understood that the nomenclature top wall, bottom wall, side walls, is intended to distinguish the walls from each other and resonators may function in any orientation relative to the Earth.

[0030] The equivalent circuit 14 to this resonator structure 2 is shown in Figure 2.

Equivalent Circuit Analysis

[0031] Figure 2 corresponds to two of the resonators each represented by their own equivalent - parallel LC (inductor-capacitor) - circuit connected through an admittance transformer, Y_t.

[0032] The resonant frequency of each resonator is obtained from the condition that the admittance of the parallel circuit, Y_0, is equal to zero

$$Y_0 = j\omega_0 C_0 + \frac{1}{j\omega_0 L_0} = 0 \quad (1)$$

to yield $\omega_0 = \frac{1}{\sqrt{L_0 C_0}}$.

[0033] The resonant frequency of the circuit shown in Figure 2 is, similarly, obtained from the condition that the input admittance, Y_{in}, is equal to zero. In order to do so, the expression for Y_{in} is obtained:

$$Y_{in} = \frac{1}{j\omega L_0} + j\omega\left(C_0 + \frac{L_0 Y_t^2}{1 - \omega^2 L_0 C_0}\right) \quad (2)$$

[0034] It is then inferred from equation (2) that the first term on the right corresponds to the susceptance of inductor L_0, while the second term represents the equivalent capacitive susceptance, composed of the susceptance of capacitor C_0 and the susceptance contribution of the second resonator. The susceptance contribution of the second resonator is of capacitive character for frequencies below the resonant frequency of the individual resonators, $\omega_0 = \frac{1}{\sqrt{L_0 C_0}}$, and of inductive character for frequencies above the resonant frequency of the individual resonators. The resonant frequencies of the resonator structure shown in Figure 2 are obtained by setting $Y_{in} = 0$, to yield

$$\left(\omega^2 L_0 C_0 - 1 - \omega L_0 Y_t\right)\left(\omega^2 L_0 C_0 - 1 + \omega L_0 Y_t\right) = 0 \quad (3).$$

[0035] Since (3) is a polynomial of order four, it has four roots, two out of which are always negative and the remaining two are positive. Discarding the negative roots as unphysical, the two positive roots are

$$\omega_1 = \frac{L_0 Y_t + \sqrt{L_0^2 Y_t^2 + 4 L_0 C_0}}{2 L_0 C_0} \quad \text{and} \quad \omega_2 = \frac{-L_0 Y_t + \sqrt{L_0^2 Y_t^2 + 4 L_0 C_0}}{2 L_0 C_0} \quad (4).$$

[0036] Equation (4), upon substitution of $\omega_0 = \frac{1}{\sqrt{L_0 C_0}}$, becomes

$$\omega_1 = \omega_0 \frac{\left(\sqrt{\left(\omega_0^2 L_0^2 Y_t^2 + 4\right)} + L_0 \omega_0 Y_t\right)}{2} \text{ and } \omega_2 = \omega_0 \frac{\left(\sqrt{\left(\omega_0^2 L_0^2 Y_t^2 + 4\right)} - L_0 \omega_0 Y_t\right)}{2} \quad (5).$$

[0037] Equation (5) indicates that the introduction of an admittance transformer, Y_t, results in two resonant frequencies: one above and the other below the resonant frequency of an individual resonator. In other words, for a given resonant frequency of an individual resonator post, the resonant frequencies of the resonator structure 2 shown in Figure 2 can be adjusted by a selection of the admittance transformer, Y_t.

[0038] The frequency difference between the two roots of (4) or (5) may be written as

$$\Delta\omega = \frac{Y_t}{2C_0} = \frac{\omega_0^2 L_0}{2} Y_t \quad (6)$$

which states that the frequency separation between the two resonant frequencies is proportional to the admittance transformation between the two resonators. It is realised that this enables a way of obtaining frequency tunability, which, rather than focusing on the variation of the equivalent capacitance of a single resonator, introduces frequency tunability as a function of the coupling between two adjacent resonators. By way of illustration, as a numerical example, considering the resonator structure shown in Figure 2, where each of the resonator posts is operating at a frequency of 2 GHz. In this example, Figure 3 shows frequency variation as a function of transformer impedance, $Z_t = \frac{1}{Y_t}$ according to equation (5). The admittance transformer, Y_t, is allowed to vary from 0.0033 S (equivalent to 300 Ω) to 0.05 S (equivalent to 20 Ω). In Figure 3, circles represent resonant frequency of each of the two resonator posts 4,6, squares represent the lower bound to the operating frequency range, and triangles represent the upper bound to the operating frequency range.

[0039] As seen in Figure 3, it is realised that, frequency tunability is obtained by controlling the impedance transformation between the two resonator posts.

[0040] It is also realised that by using two resonator posts not only is frequency tunability achievable, but also the frequency of operation is reduced, leading to reduced physical dimensions (miniaturization).

Electromagnetic Conditions

[0041] This leads to consider electromagnetic conditions that must be satisfied.

[0042] It follows from electromagnetic theory that for the coupling between two resonator posts to be strong, they must be placed in the vicinity of each other. The term "coupling" represents the amount of energy that one resonator post intercepts from another resonator post and can be expressed equally well by an equivalent loading "impedance" that one resonator post exhibits when another resonator post is placed in its vicinity.

[0043] In particular, the higher the equivalent loading "impedance" of a resonator post, the less amount of coupling exists between the two adjacently placed resonator posts. In the limiting case, when the loading impedance is infinite, no coupling exists between the resonator posts. In practice, this corresponds to the case of infinite physical separation between resonator posts.

Resonator Structure

[0044] In view of the above it is realised that a strong but controllable coupling between the two posts 4, 6 in the resonant cavity 12 is obtained by placing the resonator posts in the vicinity of each other such that one resonator post 4 extends from the bottom 8 of the cavity 10 and one resonator post 6 extends from the top 12.

[0045] Looking further at the resonator structure shown in Figure 1, it is seen that the resonators are positioned at opposite sides from each other. This means that the directions of the surface currents on the respective resonator posts 4,6 are such that the magnetic fields created by these two currents reinforce each other in the space 16 between the resonators. This implies that the coupling between the two resonator posts 4, 6 is strong, the resonator posts 4,6 exhibit a great deal of influence on each other, and this influence can be controlled by manipulating the amount of coupling between the two resonator posts 4,6. As explained earlier with reference to Figure 2, coupling can be represented by an equivalent impedance/ admittance transformer between the two resonators.

[0046] It can be considered that depending on the coupling between the two resonators, this notional impedance/ admittance transformer has a tunable electrical length.

[0047] Furthermore, given that each individual resonator post has an electrical length of 90° in isolation and that the electrical length of the transformer is adjustable, the overall electrical length of the resonant structure shown in Figure 1 can be arbitrarily long, resulting in reduced frequencies of operation compared to a single resonator in isolation.

[0048] By adjusting the coupling between two resonators, one not only significantly alters the frequency of operation of the individual resonator posts, but also makes the resonant structure widely tuneable.

[0049] Figure 4 illustrates an arrangement of an existing mini-coax resonator; (a) is an isometric view and (b) is a top view. The resonator 20a is itself a distributed resonator of second order, consisting of two resonant elements 4a, 6a similar to the arrangement described above and is referred to as a split resonator. Each resonant element 4a, 6a is cylindrical. Resonant element 4a is electrically coupled to the bottom 8a of the resonant cavity 10a, while resonant element 6a coupled to the top 12a of the resonant cavity 10a. The two resonant elements 4a, 6a are separated by a gap 30a.

Distributed Resonator - 25 elements

[0050] Figure 5 illustrates a distributed resonator 20b with 25 individual resonator elements according to one embodiment; (a) is an isometric view and (b) is a top view.

[0051] The 25 individual resonator elements are arranged in a circular grid where the individual resonator elements are arranged concentrically, in an inter-digitated fashion. In particular, three tubular structures 50b1, 50b2, 50b3 are provided. The diameter and circumference of each of the three tubular structures 50b1, 50b2, 50b3 differ. The three tubular structures 50b1, 50b2, 50b3 are axially aligned and so share a common axis. Accordingly the three tubular structures 50b1, 50b2, 50b3 are nested together, coaxially located and occupy a space similar to that of the mini-coax resonator mentioned above.

[0052] Each tubular structure 50b1, 50b2, 50b3 is made up of a number of resonant elements extending around a circumference of that tubular structure 50b1, 50b2, 50b3. In particular, the tubular structure 50b1 is formed by 8 resonant elements 6b1 to 6b4 and 4b1 to 4b4. Each resonant element is separated by an intra-structure gap 30b. In this embodiment, the intra-structure gap 30b is identical between each adjacent resonant element within that tubular structure 50b1. The resonant elements 4b1 to 4b4 are electrically coupled to the bottom 8b of the resonant cavity 10b, while resonant elements 6b1 to 6b4 are electrically coupled to the top 12b of the resonant cavity 10b. The resonant elements 6b1 to 6b4 and 4b1 to 4b4 alternate around the tubular structure 50b1 to form an interdigitated arrangement. The resonant elements 6b1 to 6b4 and 4b1 to 4b4 have a cross-sectional area defined by an arc of an annulus. Opposing faces of adjacent resonant elements separated by the intra-structure gap 30b are symmetric about that intra-structure gap 30b. Typically, these opposing faces will be slightly rounded to improve current flow within the resonant elements.

[0053] Tubular structures 50b2 and 50b3 have a similar configuration to tubular structure 50b1, but with a different diameter and therefore circumference. The differing diameter provides for an inter-structure gap 40b between adjacent tubular structures. In this embodiment, the inter-structure gap 40b is constant between each adjacent tubular structure. Adjacent tubular structures are arranged so that resonant elements from one tubular structure which are coupled to the bottom 8b of the resonant cavity 10b are adjacent resonant elements of the adjacent tubular structure which are electrically coupled to the top 12b of the resonant cavity 10b.Thus, the resonant elements alternate radially between tubular structures to also form an interdigitated arrangement. In this arrangement, the intra-structure gaps 30b of adjacent tubular structures are aligned and extend radially.

[0054] The axially-central position is occupied by a tuning screw 60b, which acts as one of the resonant elements.

[0055] In operation, a signal is received via an input signal feed (not shown) within the resonant cavity 10b. The input signal feed magnetically couples with a resonator element, which in turn magnetically couples across its intra-structure gaps 30b with adjacent resonator elements and across its inter-structure gap 40b with an adjacent resonator element of an adjacent tubular structure. The magnetic coupling then continues between the resonator element and the signal distributes across the array. A filtered signal is then received at an output signal feed (not shown).

[0056] This arrangement of individual resonator elements has the following advantages:

1. This offers extreme low-profile, improved over the arrangements in Figures 2 and 3, but with substantial high performance.
2. Due to the inter-digitated nature of the individual resonators along the circumference of each concentric circular grid, there exists a strong coupling among the resonators along the perimeter of the grid.
3. Due to the inter-digitated nature of the individual resonators in the radial direction, there exists a strong coupling is this direction, which, together with 1., allows for an additional level of miniaturization as compared with the arrangement of Figure 2.
4. The use of inter-digitated resonators along the circumference of each circular grid offers an additional degree of freedom, epitomized in the relative rotation of one set of inter-digitated resonators along the perimeter with respect to its neighbouring set.

[0057] The arrangement of the distributed resonator of Figure 5 is only one of the possible realizations. For example, the number of resonator elements along the perimeter need not be 8, but any integer number would suffice. For a greater level of miniaturization, the number of resonator elements along the perimeter need to be even and may be odd.

Distributed Resonator - 17 elements

[0058] Figure 6 illustrates a distributed resonator 20c with 17 individual resonator elements according to one embodiment; (a) is an isometric view and (b) is a top view.

[0059] Out of the 17 resonator elements, 16 are arranged in a circular grid, while the last, 17th element is a tuning screw 60c which occupies the central position for fine frequency adjustments.

[0060] The 17 individual resonator elements are arranged in a circular grid where the individual resonator elements are arranged concentrically, in an inter-digitated fashion. In particular, two tubular structures 50c1, 50c2 are provided. The diameter and circumference of the two tubular structures 50c1, 50c2 differ. The two tubular structures 50c1, 50c2 are axially aligned and so share a common axis. Accordingly the two tubular structures 50c1, 50c2 are nested together, coaxially located and occupy a space similar to that of the mini-coax resonator mentioned above.

[0061] Each tubular structure 50c1, 50c2 is made up of a number of resonant elements extending around a circumference of that tubular structure 50c1, 50c2. In particular, the tubular structure 50c1 is formed by 8 resonant elements 6c1 to 6c4 and 4c1 to 4c4. Each resonant element is separated by an intra-structure gap 30c. In this embodiment, the intra-structure gap 30c is identical between each adjacent resonant element within that tubular structure 50c1. The resonant elements 4c1 to 4c4 are electrically coupled to the bottom 8c of the resonant cavity 10c, while resonant elements 6c1 to 6c4 are electrically coupled to the top 12c of the resonant cavity 10c. The resonant elements 6c1 to 6c4 and 4c1 to 4c4 alternate around the tubular structure 50c1 to form an interdigitated arrangement. The resonant elements 6c1 to 6c4 and 4c1 to 4c4 have a cross-sectional area defined by an arc of an annulus. Opposing faces of adjacent resonant elements separated by the intra-structure gap 30c are symmetric about that intra-structure gap 30c. Typically, these opposing faces will be slightly rounded to improve current flow within the resonant elements.

[0062] Tubular structure 50c2 has a similar configuration to tubular structure 50c1, but with a different diameter and therefore circumference. The differing diameter provides for an inter-structure gap 40c between adjacent tubular structures. In this embodiment, the inter-structure gap 40c is constant between each adjacent tubular structure. Adjacent tubular structures are arranged so that resonant elements from one tubular structure which are coupled to the bottom 8c of the resonant cavity 10c are adjacent resonant elements of the adjacent tubular structure which are electrically coupled to the top 12c of the resonant cavity 10c. Thus, the resonant elements alternate radially between tubular structures to also form an interdigitated arrangement. In this arrangement, the intra-structure gaps 30c of adjacent tubular structures are aligned and extend radially.

[0063] The axially-central position is occupied by a tuning screw 60c, which acts as one of the resonant elements.

[0064] In operation, a signal is received via an input signal feed (not shown) within the resonant cavity 10c. The input signal feed magnetically couples with a resonator element, which in turn magnetically couples across its intra-structure gaps 30c with adjacent resonator elements and across its inter-structure gap 40c with an adjacent resonator element of an adjacent tubular structure. The magnetic coupling then continues between the resonator element and the signal distributes across the array. A filtered signal is then received at an output signal feed (not shown).

[0065] The resonator of Figure 6 is made to operate at the frequency of 2.3 GHz and its dimensions are 40 mm x 40 mm x 5 mm. The frequency of operation of the resonator of Figure 6 has been compared to the frequency of operation of the resonator of Figure 3 having the same dimensions. In particular, the radial separation of the concentric circular grids in the case of the resonator of Figure 6 is the same as the radial separation of the concentric cylinders of the resonator of Figure 3.

[0066] Table 1 compares the frequencies of operation of the resonators. The reported resonant-frequency values were obtained by utilizing the full-wave analysis software tool of CST Studio Suite.

Table 1: Comparison of resonant frequencies of distributed resonators

Resonator type	Resonant frequency, f_0 [MHz]	Volume (mm^3)
Figure 6 Resonator	2350	40x40x5
Figure 3 Resonator	2778	40x40x5

[0067] As evident from this table, the resonator of Figure 6 offers a reduction in the frequency of operation of over 15 % as compared to the frequency of operation of resonator of Figure 3 having the same dimensions. Further, if the frequency of operation of the two resonators is made to be identical, the separation of the distributed elements of the resonator of Figure 6 will be much greater than the separation among the concentric cylinders of the traditional mini-coax resonator, which indicates that the resonator of Figure 6 is capable of greater power handling capability.

Distributed Resonator - 25 offset elements

[0068] Figure 7 illustrates a distributed resonator 20c with 25 individual resonator elements according to one embodiment; (a) is an isometric view and (b) is a top view.

[0069] The 25 individual resonator elements are arranged in a circular grid where the individual resonator elements are arranged concentrically, in an inter-digitated fashion. In particular, three tubular structures 50d1, 50d2, 50d3 are provided. The diameter and circumference of each of the three tubular structures 50d1, 50d2, 50d3 differ. The three tubular structures 50d1, 50d2, 50d3 are axially aligned and so share a common axis. Accordingly the three tubular structures 50d1, 50d2, 50b3 are nested together, coaxially located and occupy a space similar to that of the mini-coax resonator mentioned above.

[0070] This arrangement is identical to that shown in Figure 5 with the exception that the resonator elements of the tubular structure 50d2 are circumferentially offset from the resonator elements of the tubular structures 50d1, 50d3. This means that the intra-structure gaps 30d are not radially aligned.

[0071] In operation, a signal is received via an input signal feed (not shown) within the resonant cavity lOd. The input signal feed magnetically couples with a resonator element, which in turn magnetically couples across its intra-structure gaps 30d with adjacent resonator elements and across its inter-structure gap 40d with an adjacent resonator element of an adjacent tubular structure. The magnetic coupling then continues between the resonator element and the signal distributes across the array. A filtered signal is then received at an output signal feed (not shown).

[0072] It will be appreciated that the benefits regarding frequency tunability of the existing mini-coax resonator are carried over to the resonator of embodiments. In other words, the miniaturized coaxial distributed resonator offers a better utilization of the available volume compared to the traditional mini-coax resonator, while retaining the attractive frequency tunability benefits.

[0073] It will also be appreciate that the distributed resonator of embodiments can, without any loss of generality, be applied in a number of realizations. For example, any number of individual elements can be provided along the circumference. However, as stated earlier, this number should preferably be even. Also, any number of concentric rings can be provided and is only influenced by design requirements.

[0074] Although in some of the embodiments mentioned above, the intra-structure gaps are aligned radially, it will be appreciated that need not align. Also, differing width intra-structure gaps and inter-structure gaps may be provided as influenced by design requirements.

[0075] Also, it will be appreciated that other than circular tubular structures maybe provided such as polyhedral prisms, annular or elliptical prisms. Accordingly, the resonant elements may have other than annual cross section, such as polygon or curved cross section

[0076] Embodiments provide for reduced physical dimensions of cavity filters. This quality is greatly valued in industrial applications. Size reduction can be achieved using distributed resonance provided by embodiments. Embodiments further enhance performance and provide a suitable, practical means to further reduce size without compromising frequency tunability and performance.

[0077] Embodiments have particular utility in the field of Remote Radio Heads, where smaller and lighter-weight filters result in a smaller wind load as well as reduced load-bearing requirements on the mounting mast/tower.

[0078] A person of skill in the art would readily recognize that steps of various above-described methods can be performed by programmed computers. Herein, some embodiments are also intended to cover program storage devices, e.g., digital data storage media, which are machine or computer readable and encode machine-executable or computer-executable programs of instructions, wherein said instructions perform some or all of the steps of said above-described methods. The program storage devices maybe, e.g., digital memories, magnetic storage media such as a magnetic disks and magnetic tapes, hard drives, or optically readable digital data storage media. The embodiments are also intended to cover computers programmed to perform said steps of the above-described methods.

[0079] The functions of the various elements shown in the Figures, including any functional blocks labelled as "processors" or "logic", may be provided through the use of dedicated hardware as well as hardware capable of executing software in association with appropriate software. When provided by a processor, the functions may be provided by a single dedicated processor, by a single shared processor, or by a plurality of individual processors, some of which may be shared. Moreover, explicit use of the term "processor" or "controller" or "logic" should not be construed to refer exclusively to hardware capable of executing software, and may implicitly include, without limitation, digital signal processor (DSP) hardware, network processor, application specific integrated circuit (ASIC), field programmable gate array (FPGA), read only memory (ROM) for storing software, random access memory (RAM), and non-volatile storage. Other hardware, conventional and/or custom, may also be included. Similarly, any switches shown in the Figures are conceptual only. Their function may be carried out through the operation of program logic, through dedicated logic, through the interaction of program control and dedicated logic, or even manually, the particular technique being selectable by the implementer as more specifically understood from the context.

[0080] It should be appreciated by those skilled in the art that any block diagrams herein represent conceptual views of illustrative circuitry embodying the principles of the invention. Similarly, it will be appreciated that any flow charts, flow diagrams, state transition diagrams, pseudo code, and the like represent various processes which may be substantially represented in computer readable medium and so executed by a computer or processor, whether or not such computer or processor is explicitly shown.

[0081] The description and drawings merely illustrate the principles of the invention. It will thus be appreciated that those skilled in the art will be able to devise various arrangements that, although not explicitly described or shown herein, embody the principles of the invention and are included within its spirit and scope. Furthermore, all examples recited herein are principally intended expressly to be only for pedagogical purposes to aid the reader in understanding the principles of the invention and the concepts contributed by the inventor(s) to furthering the art, and are to be construed as being without limitation to such specifically recited examples and conditions. Moreover, all statements herein reciting principles, aspects, and embodiments of the invention, as well as specific examples thereof, are intended to encompass equivalents thereof.

Claims

1. A resonator, comprising:

a resonant chamber defined by a first wall, a second wall opposing said first wall and side walls extending between said first wall and said second wall;
a plurality of concentric tubular structures, each tubular structure being formed by a first resonant element and a second resonant element separated by an intra-structure gap and located in proximity with each other for magnetic field coupling between said first resonant element and said second resonant element, said first resonant element being grounded on said first wall and extending into said resonant chamber from said first wall, said second resonant element being grounded on said second wall and extending into said resonant chamber from said second wall, each tubular structure being separated by an inter-structure gap and located in proximity with each other for magnetic field coupling between first and second resonant elements of adjacent tubular structures.

2. The resonator of claim 1, wherein said first resonant element and said second resonant elements comprise a pair of resonant elements and each tubular structure comprises a plurality of pairs of resonant elements.

3. The resonator of claim 2, wherein said plurality of pairs of resonant elements extend circumferentially around said tubular structure.

4. The resonator of any preceding claim, wherein said first resonant elements and said second resonant elements alternate circumferentially around said tubular structure.

5. The resonator of any preceding claim, wherein said first and said second resonant elements define constant intra-structure gaps.

6. The resonator of any preceding claim, wherein said first and said second resonant elements are symmetric about their intra-structure gap.

7. The resonator of any preceding claim, wherein said first and said second resonant elements have one of a polygonal and curved cross-sectional area.

8. The resonator of any preceding claim, wherein said first and said second resonant elements are elongate.

9. The resonator of any preceding claim, wherein said first and second resonant elements define cylindrical segments extending along a central axis.

10. The resonator of any preceding claim, wherein said plurality of concentric tubular structures are radially displaced with respect to each other.

11. The resonator of any preceding claim, wherein said first and said second resonant elements of adjacent tubular structures alternate radially, each separated by said inter-structure gap.

12. The resonator of any preceding claim, wherein said first and second resonant elements of adjacent tubular structures define constant inter-structure gaps.

13. The resonator of any preceding claim, wherein intra-structure gaps of adjacent tubular structures are radially aligned.

14. The resonator of any preceding claim, comprising a tuning screw concentrically located within an innermost tubular structure.

15. A method of radio frequency filtering, comprising passing a signal for filtering through at least one resonator as claimed in any preceding claim.

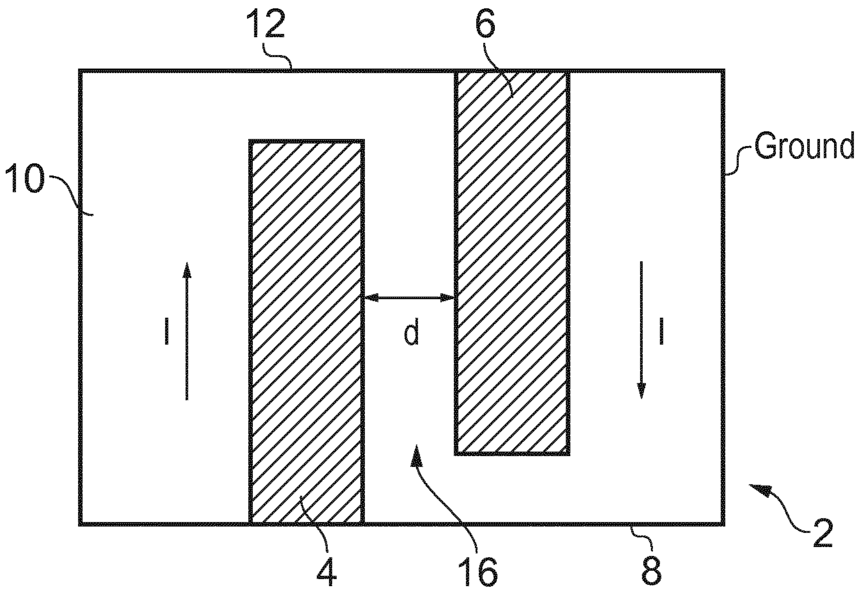


FIG. 1

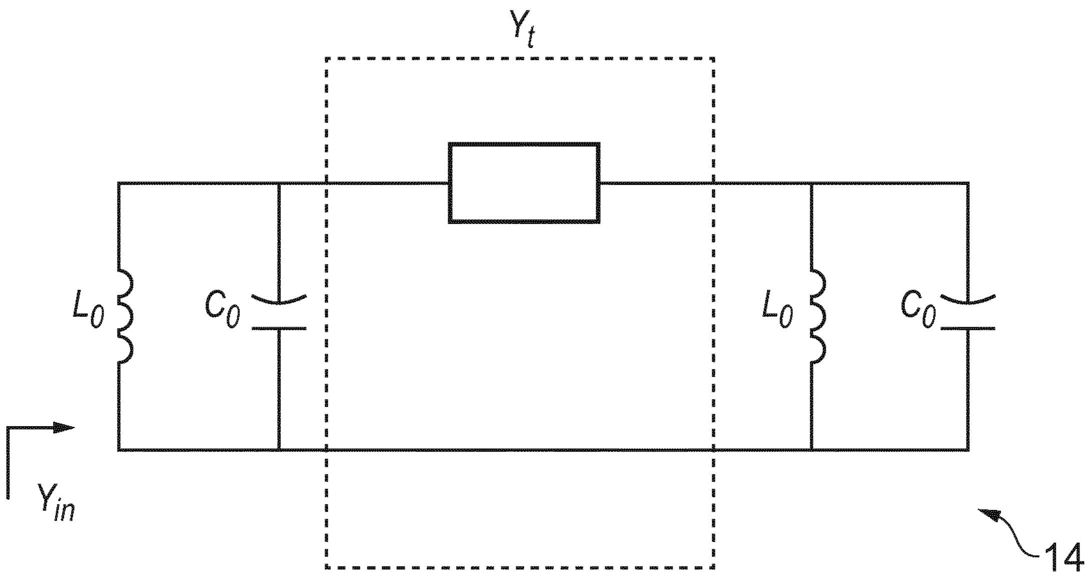


FIG. 2

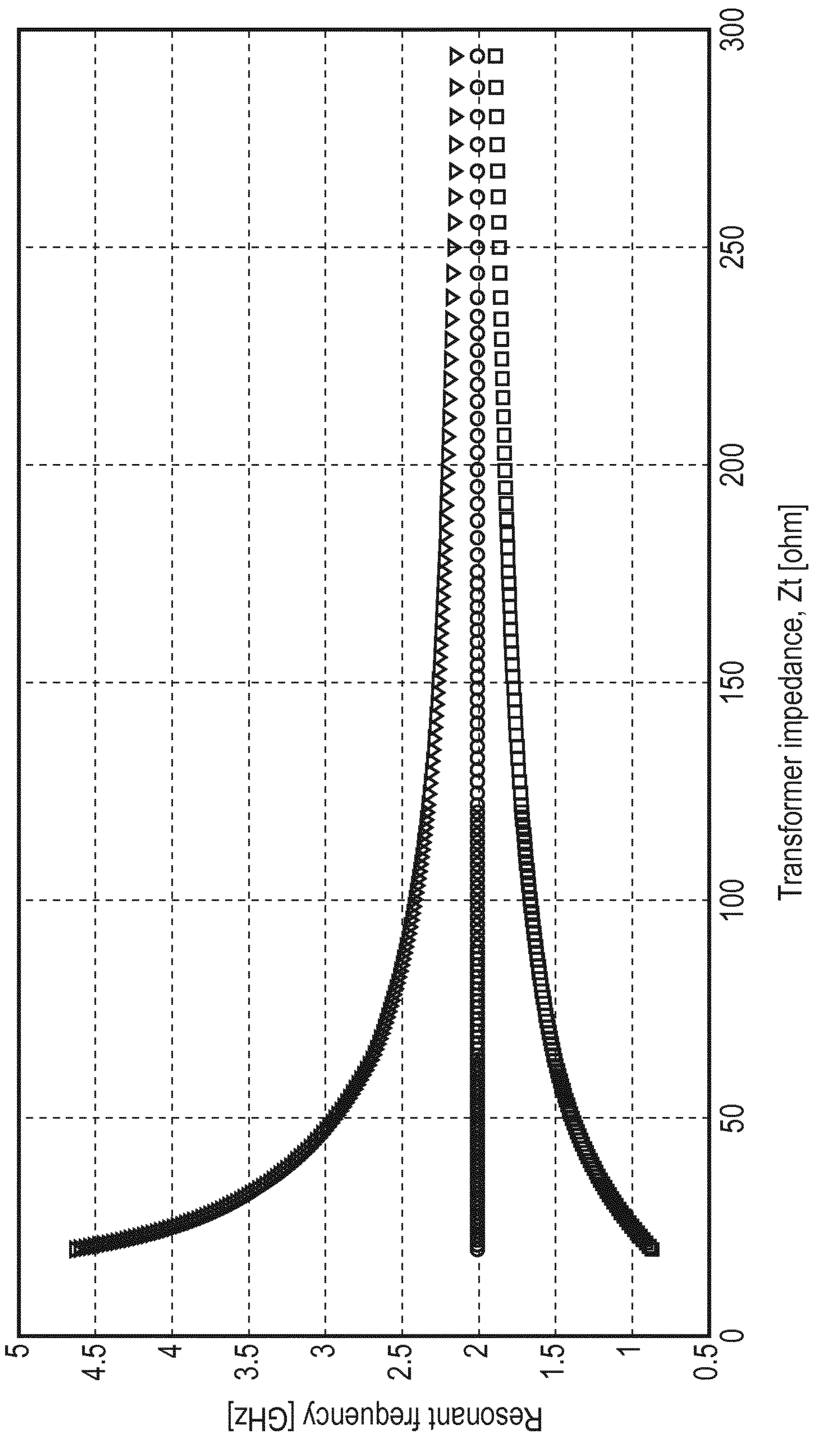

Resonant frequency [GHz]
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Transformer impedance, Zt [ohm]
0
50
100
150
200
250
300

FIG. 3

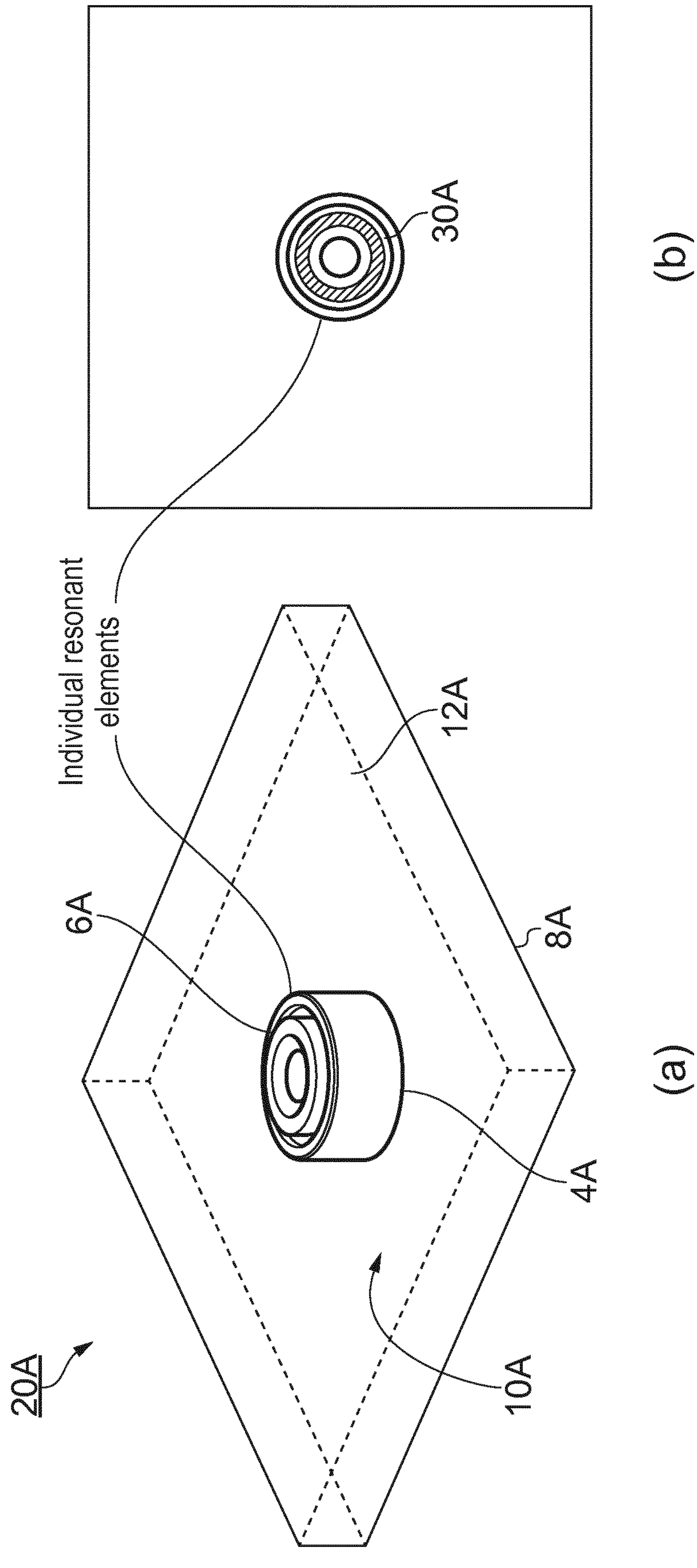


FIG. 4

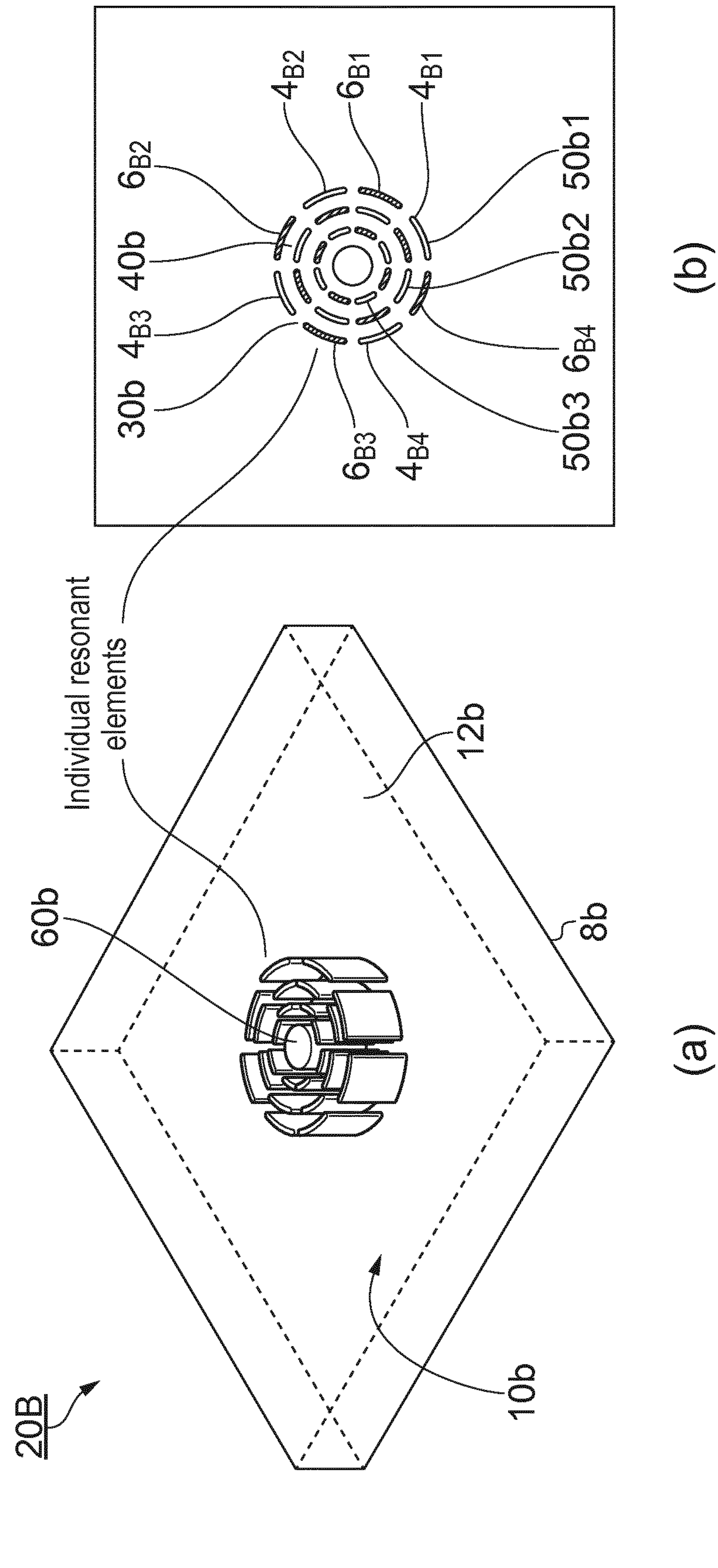
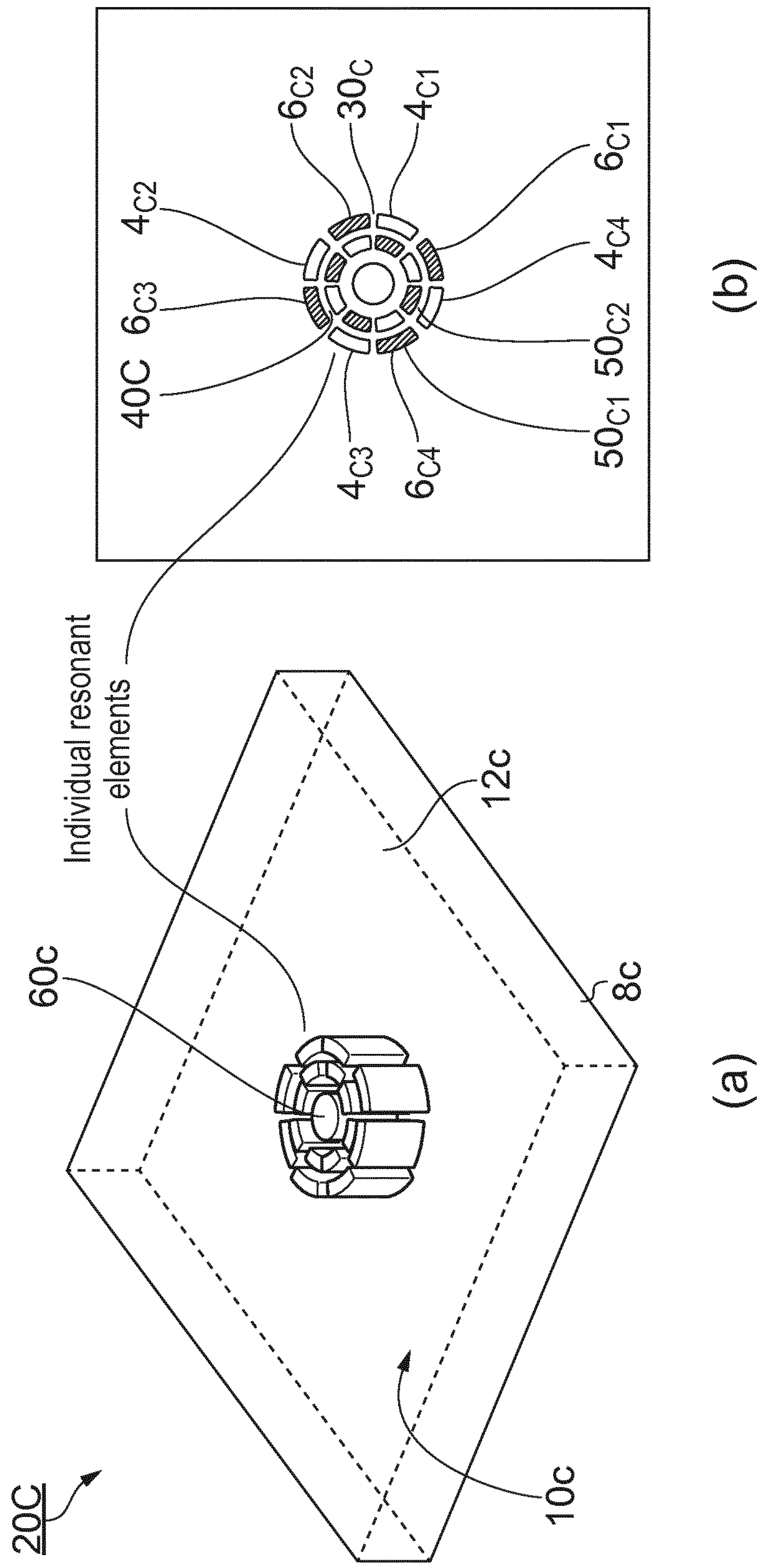

20B
10b
8b
12b
60b
Individual resonant elements
(a)
30b
4_{B3}
40b
6_{B2}
4_{B2}
6_{B1}
4_{B1}
50b1
50b2
50b3
6_{B4}
6_{B3}
4_{B4}
(b)

FIG. 5


20C
10c
8c
12c
60c
Individual resonant elements
(a)
40C
6_{C3}
4_{C2}
6_{C2}
30_C
4_{C1}
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4_{C4}
50_{C2}
50_{C1}
6_{C4}
4_{C3}
(b)

FIG. 6

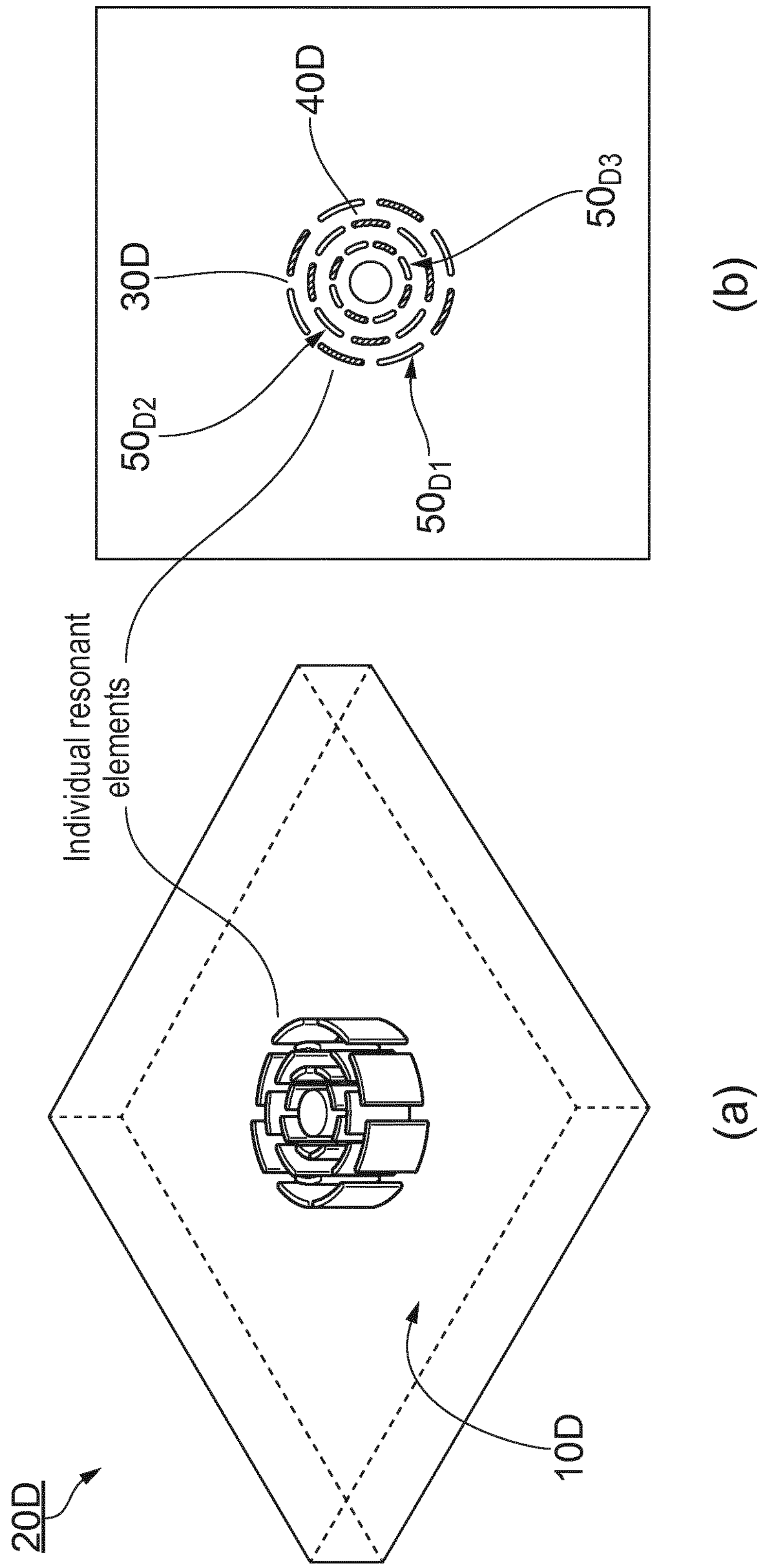
20D
10D
Individual resonant elements
(a)
30D
40D
50_{D1}
50_{D2}
50_{D3}
(b)

FIG. 7

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EUROPEAN SEARCH REPORT

Application Number
EP 16 19 1178

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X	EP 3 012 901 A1 (ALCATEL LUCENT [FR]) 27 April 2016 (2016-04-27) * paragraphs [0019], [0050] - paragraph [0063]; figure 8 * -----	1,4-9, 14,15	INV. H01P1/205 H01P7/04
X	US 3 980 920 A (DUDLEY KENNETH W ET AL) 14 September 1976 (1976-09-14) * column 1 - column 3; figures 1, 2 * -----	1-13,15	
X	EP 3 012 902 A1 (ALCATEL LUCENT [FR]) 27 April 2016 (2016-04-27) * paragraphs [0049], [0074] - paragraph [0100]; figures 9, 12, 13 * -----	1-8,10, 11,14,15	
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TECHNICAL FIELDS SEARCHED (IPC)

H01P

The present search report has been drawn up for all claims

1

Place of search	Date of completion of the search	Examiner
The Hague	27 March 2017	Hueso González, J

CATEGORY OF CITED DOCUMENTS

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27-03-2017

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For more details about this annex : see Official Journal of the European Patent Office, No. 12/82