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(54) Title: REDUCING IMPACT ON INSERTION LOSS OF APERTURES IN CONDUCTIVE COVERING OF FILTER BODY

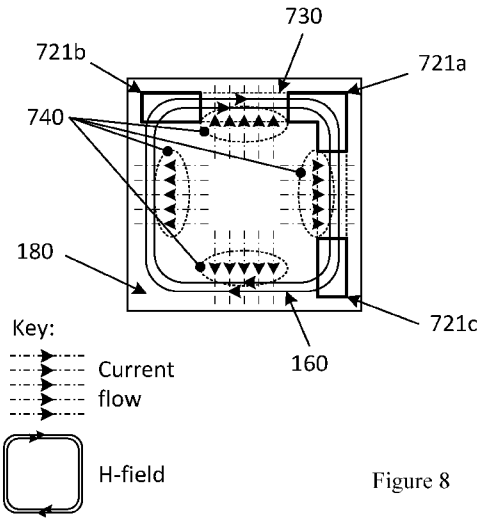



Figure 8

(57) Abstract: A multi-mode cavity filter, comprising: at least two dielectric resonator bodies, the first dielectric resonator body incorporating a piece of dielectric material, the piece of dielectric material having a shape such that it can support at least a first resonant mode and at least a second substantially degenerate resonant mode;the second dielectric resonator body also comprising a piece of dielectric material, the dielectric properties, shape and dimensions of which may differ from those of the first dielectric resonator body;the said second piece of dielectric material having a shape such that it can support at least a first resonant mode; a layer of conductive material in contact with and covering both of the dielectric resonator bodies; at least one aperture in the layer or layers of conductive material appearing at the interface of the first dielectric resonator body and the second dielectric resonator body, for at least one of: transferring signals from the second dielectric resonator body to the first dielectric resonator body, transferring signals from the first dielectric resonator body to the second dielectric resonator body and outputting signals from the first dielectric resonator body, the at least one aperture being arranged for at least one of directly coupling signals to the first resonant mode and the second substantially degenerate resonant mode existing within the first dielectric resonator,in parallel, and directly coupling signals from the first resonant mode and the second substantially degenerate resonant mode existing within the first dielectric resonator, in parallel.

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# REDUCING IMPACT ON INSERTION LOSS OF APERTURES IN CONDUCTIVE COVERING OF FILTER BODY

## Technical field

The present invention relates to filters, and in particular to a multi-mode filter including a resonator body for use, for example, in frequency division duplexers for telecommunication applications.

## Background

The reference in this specification to any prior publication (or information derived from it), or to any matter which is known, is not, and should not be taken as an acknowledgment or admission or any form of suggestion that the prior publication (or information derived from it) or known matter forms part of the common general knowledge in the field of endeavour to which this specification relates.

All physical filters essentially consist of a number of energy storing resonant structures, with paths for energy to flow between the various resonators and between the resonators and the input/output ports. The physical implementation of the resonators and the manner of their interconnections will vary from type to type, but the same basic concept applies to all. Such a filter can be described mathematically in terms of a network of resonators coupled together, although the mathematical topography does not have to match the topography of the real filter.

Conventional single-mode filters formed from dielectric resonators are known. Dielectric resonators have high-Q (low loss) characteristics which enable highly selective filters having a reduced size compared to cavity filters. These single-mode filters tend to be built as a cascade of separated physical dielectric resonators, with various couplings between them and to the ports. These resonators are easily identified as distinct physical objects, and the couplings tend also to be easily identified.

Single-mode filters of this type may include a network of discrete resonators formed from ceramic materials in a "puck" shape, where each resonator has a single dominant resonance frequency, or mode. These resonators are coupled together by providing openings between cavities in which the resonators are located. Typically, the resonators and cross-couplings provide transmission poles and "zeros", which can be tuned at particular frequencies to provide a desired filter response. A number of resonators will usually be required to achieve suitable filtering characteristics for commercial applications, resulting in filtering equipment of a relatively large size.

One example application of filters formed from dielectric resonators is in frequency division duplexers for microwave telecommunication applications. Duplexers have traditionally been provided at base stations at the bottom of antenna supporting towers, although a current trend for microwave telecommunication system design is to locate filtering and signal processing equipment at the top of the tower to thereby minimise cabling lengths and thus reduce signal losses. However, the size of single mode filters as described above can make these undesirable for implementation at the top of antenna towers.

Multi-mode filters implement several resonators in a single physical body, such that reductions in filter size can be obtained. As an example, a silvered dielectric body can resonate in many different modes. Each of these modes can act as one of the resonators in a filter. In order to provide a practical multi-mode filter it is necessary to couple the energy between the modes within the body, in contrast with the coupling between discrete objects in single mode filters, which is easier to control in practice.

The usual manner in which these multi-mode filters are implemented is to selectively couple the energy from an input port to a first one of the modes. The energy stored in the first mode is then coupled to different modes within the resonator by introducing specific defects into the shape of the body. In this manner, a multi-mode filter can be implemented as an effective cascade of resonators, in a similar way to conventional single mode filter implementations. This technique results in transmission poles which can be tuned to provide a desired filter response.

An example of such an approach is described in U.S. Patent No. 6,853,271, which is directed towards a triple-mode mono-body filter. Energy is coupled into a first mode of a dielectric-filled mono-body resonator, using a suitably configured input probe provided in a hole formed on a face of the resonator. The coupling between this first mode and two other modes of the resonator is accomplished by selectively providing corner cuts or slots on the resonator body.

This technique allows for substantial reductions in filter size because a triple-mode filter of this type represents the equivalent of a single-mode filter composed of three discrete single mode resonators. However, the approach used to couple energy into and out of the resonator, and between the modes within the resonator to provide the effective resonator cascade, requires the body to be of complicated shape, increasing manufacturing costs.

An alternative manner in which these multi-mode filters may be implemented is to couple the energy from an input port, simultaneously to each one of the modes, by means of a suitably designed coupling track. Again, in this manner, a multi-mode filter can be implemented as an effective cascade of resonators, in a similar way to conventional single mode filter implementations. As was the case above, in which defects were used to enable multiple modes to be excited in a single resonator, this technique results in transmission poles which can be tuned to provide a desired filter response. This type of filter has been disclosed in various US patent filings, for example: US 13/488,123, US 13/488,059, US 13/487,906 and US 13/488,182.

Two or more triple-mode filters may still need to be cascaded together to provide a filter assembly with suitable filtering characteristics. As described in U.S. Patent Nos. 6,853,271 and 7,042,314 this may be achieved using a single waveguide or a centrally-located single aperture for providing coupling between two resonator mono-bodies. With this approach, the precise control of the modes being coupled to, coupled from or coupled between the bodies, is difficult to achieve and thus, as a consequence, achieving a given, challenging, filter specification is difficult.

Another approach includes using a single-mode combline resonator coupled between two dielectric mono-bodies to form a hybrid filter assembly as described in U.S. Patent No. 6,954,122. In this case, the physical complexity and hence manufacturing costs are even further increased, over and above the use of added defects alone.

Summary of invention

According to an aspect of the present invention, there is provided a multi-mode cavity filter, comprising: at least one dielectric resonator body incorporating a piece of dielectric material, the piece of dielectric material having a shape such that it can support at least a first resonant mode and at least a second substantially degenerate resonant mode; a layer of conductive material in contact with and covering the dielectric resonator body; at least two apertures in the layer of conductive material and at least one gap between the at least two apertures, the at least two apertures being arranged for at least one of inputting signals to the dielectric resonator body and outputting signals from the dielectric resonator body; the at least one gap being arranged to facilitate the substantially unimpeded flow of current through the metallisation; the at least two apertures being arranged for at least one of directly coupling signals to the first resonant mode and the second substantially degenerate resonant mode in parallel, and directly coupling signals from the first resonant mode and the second substantially degenerate resonant mode in parallel.

A set of apertures in the conductive covering for effecting a coupling between electromagnetic waves inside and outside the body can be termed a "perforated zone" of the covering.

The at least two apertures may, for example, comprise at least one of an input coupling aperture and an output coupling aperture for respectively coupling signals to and from the dielectric resonator body.

The at least two apertures may, for example, consist of two or more parts, where a first part runs substantially parallel to a surface of the dielectric resonator body and a second part runs substantially perpendicular to the first part. The at least two

apertures may, for example, be placed close to at least one edge of the dielectric resonator body.

The at least two coupling apertures may, for example, each individually, or together, comprise a first portion primarily for coupling to a first mode and a second portion primarily for coupling to a second mode. The first portion of the at least two coupling apertures may, for example, be oriented such that at least one of the magnetic field and the electric field coupled by said first portion is substantially aligned with the respective magnetic field or electric field of said first mode. The second portion of the at least two coupling apertures may, for example, be oriented such that at least one of the magnetic field and the electric field coupled by said second portion is substantially aligned with the respective magnetic field or electric field of said second mode. The first portion and second portion may, for example, be any of the following: a straight, curved or amorphous aperture or a regular or irregular two-dimensional shape. The first portion may, for example, comprise a first straight elongate aperture and the second portion may, for example, comprise a second straight elongate aperture arranged substantially orthogonally to the first straight elongate aperture and which may intersect with the first straight elongate aperture or may be distinct from the first straight elongate aperture.

The at least two coupling apertures may, for example, comprise a portion for coupling simultaneously to both the first mode and the second mode. The portion may, for example, comprise an elongate aperture oriented at an angle such that at least one of the magnetic field and the electric field generated by said portion has a first Cartesian component aligned with the respective magnetic field or electric field of said first mode, and a second Cartesian component aligned with the respective magnetic field or electric field of said second mode.

The coupling apertures may, for example, be formed as an area devoid of conductive material, in the layer of conductive material.

The multi-mode cavity filter may, for example, further comprise an input resonator and an output resonator, operably-coupled to the multi-mode resonator and operable to

contain the electric and magnetic fields to be coupled into the multi-mode resonator. The input resonator and the output resonator may be made of the same material as the multi-mode resonator or they may be made from a different material.

The piece of dielectric material forming the body of the multi-mode resonator, may, for example, comprise a substantially planar surface for mounting to a planar surface on the input resonator. The piece of dielectric material forming the body of the multi-mode resonator, may also, for example, comprise a second substantially planar surface for mounting to a planar surface on the output resonator.

The coupling apertures may, for example, be provided on or adjacent to said substantially planar surface.

The input resonator may, in turn, be provided with a probe or other excitation means to enable signals to be fed into the input resonator. The output resonator may also be provided with a probe or other excitation means to enable signals to be extracted from the output resonator.

Brief description of the drawings

For a better understanding of the present invention, and to show more clearly how it may be carried into effect, reference will now be made, by way of example, to the following drawings, in which:

Figure 1a is a schematic perspective view of an example of a multi-mode filter;

Figure 1b is a schematic front-face view of the multi-mode filter of Figure 1a;

Figure 2 is a schematic perspective view of the example multi-mode filter of Figure 1a showing an example of one representative form for the electric and magnetic fields immediately outside of the front face of the multi-mode filter;

Figure 3 is a schematic perspective view of a second example of a multi-mode filter;

Figure 4 is a schematic perspective view of a third example of a multi-mode filter;

Figures 5(a) to (d) show various fields and modes outside of and within an example multi-mode resonator;

Figure 6 is a schematic perspective view of the example multi-mode filter of Figure 1 incorporating input and output coupling resonators;

Figure 7 is a schematic perspective view of an example of a multi-mode filter showing the phenomenon of 'current crowding', as will be described;

Figure 8 is a schematic view of an example of a multi-mode filter showing example field patterns;

Figure 9 is a schematic view of a further example of a multi-mode filter showing example field patterns;

Figures 10(a) to (c) are schematic diagrams of example coupling aperture arrangements for a multi-mode filter;

Figure 11(a) is a schematic diagram of an example of a duplex communications system incorporating a multi-mode filter;

Figure 11(b) is a schematic diagram of an example of the frequency response of the multi-mode filter of Figure 11(a);

Figure 12 is a schematic perspective view of an example of a multi-mode filter using multiple resonator bodies to provide filtering for transmit and receive channels;

Figure 13(a) is a schematic perspective view of an example multi-mode filter incorporating input and output coupling probes;

Figure 13(b) is a schematic diagram showing a side view of the example multi-mode filter of Figure 13(a), incorporating input and output coupling probes;

Figure 14(a) is a schematic perspective view of an example of a resonator with probe-based excitation;

Figure 14(b) is a schematic perspective view of an example of a multi-mode filter showing various fields and modes within the resonators;

Figure 14(c) is a schematic perspective view of an example multi-mode resonator showing example field orientations within the resonator;

Figure 15 is a schematic perspective view showing a further example of a multi-mode filter;

Figure 16 is a schematic perspective view showing a further example of a multi-mode filter.

Detailed description

An example of a multi-mode filter will now be described with reference to Figures 1a and 1b.

The basis of this invention is in the use of a specific type of coupling aperture to couple signals into and out of a multi-mode resonator, whilst exciting (or coupling energy from) two or more modes, simultaneously, within that resonator.

In this example, the filter 100 includes a resonator body 110 which is encapsulated in a metallised layer (which is not shown, for clarity). At least two apertures are formed in the metallised layer: an input coupling aperture 120 and an output coupling aperture 130. These apertures are constituted by an absence of metallisation, with the remainder of the resonator body being substantially encapsulated in its metallised layer. The apertures 120 and 130 may be formed by, for example, etching, either

chemically or mechanically, the metallisation surrounding the resonator body, 110, to remove metallisation and thereby form the one or more apertures. The one or more apertures could also be formed by other means, such as producing a mask in the shape of the aperture, temporarily attaching the said mask to the required location on the surface of the resonator body, spraying or otherwise depositing a conductive layer (the 'metallised layer') across substantially all of the surface area of the resonator body and then removing the mask from the resonator body, to leave an aperture in the metallisation.

The orientation of the axes which will be used, subsequently, to define the names and orientations of the various modes, within the multi-mode resonator 110, are defined by the axis diagram, 140.

Figure 1b shows a view of the face of the resonator body 110 containing an input aperture 120. Input aperture 120 is shown as being formed by an absence of the metallisation 150 on the surface of an end face (as shown) of a resonator body 110, shown in Figure 1(a).

The input aperture 120 is shown, in this example, as being composed of two orthogonal slots 121 and 122 in the metallisation 150. These two orthogonal slots 121 and 122 are shown to meet in the upper left-hand corner of the front face of the resonator body, to form a single, continuous aperture 120. The embodiment described above is only one of a large number of possible embodiments consistent with the invention. Further examples will be provided below, in which multiple separate slot apertures are used and where the said slot apertures do not meet or meet at a different location along their lengths, for example half-way along, thereby forming a cross.

Two coupling apertures are provided: one for coupling RF energy into the resonator and one for coupling RF energy from the resonator back out, for example to or from a further resonator, in each case. The further resonator could be a single-mode resonator, for example. These apertures respectively excite, or couple energy from, two or more of the simple (main) modes which the resonator structure can support. The number of modes which can be supported is, in turn, largely dictated by the shape of the resonator, although cubic and cuboidal resonators are primarily those

considered in this disclosure, thereby supporting up to three (simple, non-degenerate) modes, in the case of a cube, and up to four (simple, non-degenerate) modes, in the case of a 2:2:1 ratio cuboid. Other resonator shapes and numbers of modes which such shapes can support are also possible.

Figure 1(a) shows, by way of example, a cuboidal dielectric resonator body 110; many other shapes are possible for the resonator body, whilst still supporting multiple modes. Examples of such shapes for the resonator body include, but are not limited to: spheres, prisms, pyramids, cones, cylinders and polygon extrusions. In the case of a cube or other cuboid, each face's centre is also the respective face's centroid.

Typically the resonator body 110 includes, and more typically is manufactured from, a solid body of a dielectric material having suitable dielectric properties. In one example, the resonator body is a ceramic material, although this is not essential and alternative materials can be used. Additionally, the body can be a multi-layered body including, for example, layers of materials having different dielectric properties. In one example, the body can include a core of a dielectric material, and one or more outer layers of different dielectric materials.

The resonator body 110 usually includes an external coating of conductive material, typically referred to as a metallisation layer; this coating may be made from silver, although other materials could be used such as gold, copper, or the like. The conductive material may be applied to one or more surfaces of the body. A region of the surface, forming a coupling aperture, may be uncoated to allow coupling of signals to the resonator body.

The resonator body can be any shape, but generally defines at least two orthogonal axes, with the coupling apertures extending at least partially in the direction of each axis, to thereby provide coupling to multiple separate resonance modes.

In the current example, the resonator body 110 is a cuboid body, and therefore defines three orthogonal axes substantially aligned with surfaces of the resonator body, as shown by the axes X, Y, Z. As a result, the resonator body 110 has three dominant resonance modes that are substantially orthogonal and substantially aligned with the three orthogonal axes.

Cuboid structures are particularly advantageous as they can be easily and cheaply manufactured, and can also be easily fitted together, for example by arranging multiple resonator bodies in contact, as will be described below with reference to Figure 6. Cuboid structures typically have clearly defined resonance modes, making configuration of the coupling aperture arrangement more straightforward. Additionally, the use of a cuboid structure provides a planar surface, or face, 180 so that the apertures can be arranged in a plane parallel to, or on, the planar surface 180, with the apertures optionally being formed from an absence of the metallisation which otherwise substantially surrounds the resonator body 110.

The adjoining materials and mechanisms from which the multi-mode dielectric resonator can source electric and magnetic field energy, which can then couple into the multi-mode resonator 110, and thereby excite two or more of the multiple modes which the resonator will support, are numerous. One example, which will be described further below, is to utilise one or more additional resonators, which may be single mode resonators, to contain the required electric and magnetic fields, to be coupled into the multi-mode resonator by means of the input coupling aperture 120. Likewise, the output coupling aperture 130 may couple the energy stored in the electric and magnetic fields within the multi-mode resonator 110, from two or more of its modes, into one or more output resonators, for subsequent extraction to form the output of the filter.

Whilst the use of input and output resonators as a means to provide or extract the required fields, adjacent to the coupling apertures 120 and 130, will be described further below, there are many other mechanisms by which the required fields may be provided or extracted. One further example is in the use of a radiating patch antenna structure placed at a suitable distance from the input coupling aperture 120. A suitably designed patch can provide the required electric and magnetic fields immediately adjacent to the input coupling aperture 120, such that the aperture 120 can couple the energy contained in these fields into multiple modes simultaneously, within the multi-mode resonator body 110.

Likewise, the use of a thin layer of metallisation, such as one deposited or painted onto the resonator body 110 is only one example of the form which the metallisation

could take. A further example would be a metal box closely surrounding the resonator body 110. A yet further example could be the adhesion of thin metal sheeting or foil to the faces of the resonator body 110, with pre-cut apertures in the required locations, as described in the example of a metallisation layer, above.

In some scenarios, a single resonator body cannot provide adequate performance, for example, in the attenuation of out-of-band signals. In this instance, the filter's performance can be improved by providing two or more resonator bodies arranged in series, to thereby implement a higher-performance filter.

In one example, this can be achieved by providing two resonator bodies in contact with one other, with one or more apertures provided in the, for example, silver coatings of the resonator bodies, where the bodies are in contact. This allows the electric and magnetic fields present in the first cube to excite or induce the required fields and modes within the adjacent cube, so that a resonator body can receive a signal from or provide a signal to another resonator body.

Figure 2 shows the form of the electric field (E-field) 170 and magnetic field (H-field) 160 which are typically present immediately outside of the resonator body, when a cuboidal single-mode input resonator, of the form shown as 190 in Figure 6, is used to contain the fields to be coupled into the multi-mode resonator body 110;the E field is shown as the group of arrows 170 identified by the dashed loops. Alternative sources for the required E and H fields are possible, such as the patch antenna structure described above, and these may generate differently-shaped E and H fields to those shown in Figure 2, however the principles of coupling energy into the multi-mode resonator, from these differently-shaped fields, are the same as will be described below, when considering a single-mode input resonator of the form shown as 190 in Figure 6.

Operation of the input coupling aperture 120 can now be described with the aid of Figure 2 is as follows. Electromagnetic energy, in the form of electric (E) and magnetic (H) fields existing immediately adjacent to the outside front face 180 of the resonator, can be coupled into the resonator, via the aperture 120, in two ways. The electric field (E-field) portion of the electromagnetic energy radiates through the

aperture 120, as shown by the E-field directional arrows 170. The E-field radiation will primarily couple to the X-mode within the resonator, based upon the axis definition 140 shown in Figure 2.

The H-field close to the edges of the face is shown as being quasi-square, as indicated by the two sets of H-field arrows 160, although it typically becomes increasingly circular and weaker closer to the centre of the face, as shown. The H-field will typically be at a maximum close to the edges of the resonator face 180 and at a minimum or zero in both the centre of the resonator face 180 and in the corners of the resonator face 180. This is why the H-field is shown as having rounded, rather than square or right-angle corners. The H-field 160 will typically couple to the up to three modes which can be supported by the shape shown in Figure 2: X, Y and Z, via the two orthogonal aperture portions 121 and 122. Aperture portion 121 will primarily couple to the X and Y modes, whereas aperture portion 122 will primarily couple to the X and Z modes. It can be seen, from Figure 2, that the circulating H-field 160 has a strong horizontal component existing parallel to the uppermost edge of the resonator face 180. This strong horizontal H-field component runs parallel to the horizontal (upper) aperture portion 122; this component, as shown, is at its largest in the centre of the upper edge of the aperture 122, with the aperture position shown. This strong horizontal component will typically couple most effectively to the Z mode within the resonator, based upon the axis definition 140 shown in Figure 2. In addition, it will also typically couple strongly to the X mode by two mechanisms: H-field coupling, and E-field coupling through the aperture, as shown by the E-field directional arrows 170. These two mechanisms are in opposition to one another and it is often desirable to minimise the E-field coupling component to the X-mode and rely, as far as possible, upon the H-field component of coupling to the X-mode, in order to achieve the desired degree of X-mode coupling. One mechanism for achieving this goal will be described below, with reference to Figure 3, although other options are possible.

Again, referring to Figure 2, it is clear that the circulating H-field also has a strong component parallel to the vertical (left-hand) aperture portion 121; this component would again be at its largest in the centre of the upper edge of the aperture portion 121, with the aperture position shown. This strong vertical component will couple most effectively to the Y mode within the resonator, based upon the axis definition

140 shown in Figure 2. In addition, it will also couple strongly to the X mode by the two mechanisms described previously: H-field coupling, and E-field coupling through the whole of aperture 120, incorporating aperture portion 121, as shown by the E-field directional arrows 170. These two mechanisms are, again, in opposition to one another and it is often desirable to minimise the E-field coupling component to the X-mode and rely, as far as possible, upon the H-field component in order to achieve the desired degree of X-mode coupling.

It is possible to control the level of coupling obtained in each mode by controlling the length, width and position of the two portions of the aperture (i.e. the horizontal and vertical portions 122 and 121). Likewise, changing the angle of one or both of the aperture portions, relative to the edges of the cuboid, would also have an impact upon the coupling strength achieved; with the E and H fields and multi-mode resonator shape 110 shown, altering the angle of one of the aperture portions 121 or 122 relative to the edges of the face 180 of the resonator, whilst keeping the other aperture portion fixed, would typically reduce the amount of coupling to the Z or Y modes, respectively, with a minimum amount of coupling being achieved, to the relevant mode, when the angle of the relevant aperture section (121 or 122) reached 45 degrees to its closest edge. Beyond that point, it would typically increase the coupling to the other mode; in other words an aperture portion originally intended to couple strongly to the Y mode, for example, would then couple more strongly to the Z-mode. It would also increase the amount of E-field coupling to the X-mode, since a portion of the aperture sections 121 and 122 would now be closer to the centre of the face 180 of the resonator, where the E-field is at its strongest. As a general principle, shorter, narrower apertures, when correctly oriented with respect to the electric or magnetic fields, or both, will reduce the amount of either electric or magnetic field coupling achieved, or both, whereas longer, wider apertures will increase it, at a given aperture position relative to the centre and edges of the resonator face 180. Likewise, altering the angle of the coupling aperture or aperture portion relative to the direction of the H-field will alter the degree of coupling to the relevant mode (Y or Z), based upon the resolved vector component of the H-field in the direction of the aperture or aperture portion.

Consider, now, the general case of arbitrarily shaped E and H-fields, existing within an illuminator, for example the input single-mode resonator 190 of Figure 6, which is located adjacent to an arbitrarily-shaped multi-mode resonator, where these arbitrarily shaped E and H-fields are to be coupled into the said multi-mode resonator via one or more arbitrarily-shaped coupling apertures. The term 'illuminator' is used here to refer to any object, element or the like which can contain or emit E-fields, H-fields or both types of field. The arbitrary shape of the multi-mode resonator will result in arbitrarily-shaped field orientations being required within the multi-mode resonator to excite the resonator modes, for example the X, Y and Z-modes, existing within the said multi-mode resonator. In this example, the field orientations of both the multi-mode resonator and the illuminator are equally important in determining the degree of coupling which is achieved. Likewise, the shape, size and orientation of the one or more coupling apertures are also important.

The relationship may be explained as follows. The illuminator contains one or more modes, each with its own field pattern. The set of coupling apertures also have a series of modes, again, each with their own field pattern. Finally, the arbitrarily-shaped multi-mode resonator also has its own modes and its own field patterns. The coupling from a given illuminator mode to a given aperture mode will be determined by the degree of overlap between the illuminator and aperture field patterns. Likewise, the coupling from a given coupling aperture mode to a given multi-mode resonator mode will be given by the overlap between the aperture and multi-mode resonator field patterns. The coupling from a given illuminator mode to a given multi-mode resonator mode will therefore be the phasor sum of the couplings through all of the aperture modes. The result of this is that it is the vector component of the H-field aligning with the aperture and then with the vector component of the resonator mode which, along with the aperture size, determines the strength of coupling. If all of the vectors align, then strong coupling will generally occur; likewise, if there is a mis-alignment, for example due to one or more of the apertures not aligning either horizontally or vertically with the illuminator or resonator fields, then the degree of coupling will reduce. Furthermore, if one or more of the apertures, whilst being in perfect vector alignment, is reduced in size in the direction of the said vector alignment, then the degree of coupling will also typically reduce. In the case of the E-

field, it is mainly the cross-sectional area of the aperture and its location on the face 180 of the resonator 110 which is important in determining the coupling strength. In this manner, it is possible to carefully control the degree of coupling to the various modes within the multi-mode resonator and, consequently, the pass-band and stop-band characteristics of the resulting filter.

The E-field and H-field illuminations shown in Figure 2, indicated by the E-field directional arrows 170 and the H-field arrows 160 are based upon those which would be achieved by the placement of a single-mode dielectric resonator 190 immediately adjacent to the first face 180 of the resonator, as shown in Figure 6. Note that Figure 6 also shows metallisation 150 applied on a first resonator face 180 and also metallisation 210 applied on a second resonator face 220, but omits all other metallisation surrounding the multi-mode resonator 110 and the input single-mode resonator 190 and the output single-mode resonator 200. Figure 6 will be discussed in more detail below. Clearly, other methods of illumination of the resonator face 180 are possible. Examples include, but are not limited to: a second multi-mode resonator (whether or not multiple modes are excited within it) placed or attached immediately adjacent to the resonator face 180, antenna radiating structures, such as patch antenna structures, which may be placed immediately adjacent to the resonator face 180 or some distance from the resonator face 180 or at any location in-between and stripline or microstrip transmission lines or resonators placed immediately adjacent to the resonator face 180. Whilst these would generate different field patterns than those indicated by the reference numerals 160 and 170 in Figure 2, for the E and H-fields (the H-field may no longer be quasi-square, for example), they do not detract from the basic concept of the invention, namely that of allowing largely independent 'sampling' of the E-field and the horizontal and vertical components of the H-field to take place in a carefully designed manner, utilising orthogonal aspects of the aperture or apertures wherein the one or more apertures are designed to have elements aligned with fields of the appropriate modes of the multi-mode resonator 110 and those of the illuminator.

To summarise, the main, but not the only factors required to obtain good coupling from the H-field present immediately outside of the resonator face 180, into the resonator body 110, via the one or more aperture portions 121 and 122, are:

1. Close vector alignment between the coupling aperture portion, for example aperture portions 121 or 122 in Figure 2, and the H field of the cube mode to be excited. For example, a horizontal slot will provide good excitation to the Z mode and little excitation to the Y mode, with the modes as defined 140 in Figure 2.

2. An appreciable extension of the coupling aperture in the relevant direction (for example the horizontal direction, in the case of the Z mode).

3. The placement of the coupling aperture 120 in a region where the H-field's field strength is highest, based upon the fields present immediately adjacent to the resonator face 180, both inside and outside of the resonator body 110. When considering the fields outside of the resonator body 110, such fields could, for example, be contained within the single-mode input resonator 190, shown in Figure 6.

Whilst the approach of utilising a single, continuous, aperture 120 for exciting the multiple modes in a multi-mode resonator 110, as described above in relation to Figure 1 and Figure 2, will work satisfactorily, it can have a number of drawbacks:

Firstly, it can disturb the natural current flow through the metallisation coating the face 180 of the multi-mode resonator 110 into which the coupling aperture is etched. This current flow 740 would typically proceed linearly from the centre of the face 180 to the four Edges of the face 180, as shown in Figure 8, which will be discussed further below.

One advantageous solution to this problem is to utilise multiple aperture sub-segments, for example aperture sub-segments 721a, 721b, 721c in Figure 8 and associated 'gaps' between the aperture sub-segments, for example 730 in Figure 8, to provide the required degree of coupling to multiple modes, in a multi-mode resonator 110, whilst minimising the disturbance to the currents flowing 740 in the metallisation (not shown in Figure 8, for clarity, but shown in analogous Figure 14(b)). In contrast, when using a single, continuous aperture as shown in Figure 7, the currents flowing in the metallisation can be restricted to utilising one or more narrow pathways to flow to the Edges, and hence to the remainder of the metallisation surrounding the multi-mode resonator. Disturbing (or 'crowding') of the current flow 600 can lead to increased losses, due to the finite resistivity of the metallisation surrounding the resonator and

consequently to an increased insertion loss for the complete filter. Insertion loss is a critical parameter in most transceiver duplexer applications, for example, since it directly impacts upon the amount of the transmitter's output power which reaches, and hence radiates from, the antenna connected to the transceiver. Filter insertion loss also negatively impacts receiver noise figure and sensitivity and overall transceiver power efficiency; in the latter case, largely due to its impact upon transmit signal losses and hence the RF output power radiated from the antenna.

A second advantage is that mode rotation, resulting at least partially from the aperture or apertures, is likely to be more severe without the inclusion of gaps in the apertures, such as 730 shown in Figure 8. This means that the orthogonality of the control of the modes excited within the multi-mode resonator, which is at least partially based upon the design of the aperture sizes, shapes and their locations on the face or faces of the multi-mode resonator, will typically be poorer. In other words, when designing the filter, the use of a particular aperture orientation, for example horizontal, to predominantly excite a particular mode, for example the Y-mode, will be less effective – it will typically also provide unwanted excitation to one or more of the other modes in a manner which is difficult to predict intuitively. This can therefore increase the design time and cost for the filter.

With reference to Figure 3 and Figure 4, the above principles can now be illustrated further as follows, based upon the use of twin-aperture portions per orientation, with only the horizontal orientation being considered, for simplicity. Figure 3 and Figure 4 illustrate the use of aperture positioning in order to couple a greater or lesser amount of the H-field existing immediately adjacent to the face 180 of the resonator, but outside of the resonator body 110, to the appropriate mode existing within the multi-mode resonator body 110. Figure 3 shows twin aperture sub-segments 122a and 122b, which may, together, perform a similar function to aperture portion 122 in Figure 2. In Figure 3, the aperture sub-segments 122a and 122b are placed close to the upper edge of the resonator face 180. In Figure 4, the aperture sub-segments 122a and 122b are placed closer to the left and right-hand side edges of the resonator face 180, than they are to the upper edge of that face.

In the case illustrated in these two figures, it is the Z mode existing within the multi-mode resonator body 110 which is intended to be primarily coupled to, since the aperture sub-segments 122a and 122b are oriented horizontally. In addition significant coupling to the X-mode will also occur, however this would typically be the case irrespective of the orientation of the aperture portions 121 and 122 of Figure 2 or the aperture sub-segments 122a and 122b of Figure 3 and Figure 4, so long as they remained in the same location or locations on the resonator face 180.

In Figure 3, the aperture sub-segments 122a and 122b are shown as being relatively closely-spaced and also relatively close to the top of the resonator face 180. In this location, it can be seen that they will couple well to the strong horizontal component of the H-field, indicated by the H-field arrows 160, which is present close to the top of the resonator face 180. The H-field arrows 160 align, vectorially, in the same orientation as the aperture sub-segments 122a and 122b and thereby strong coupling to the Z mode present within the multi-mode resonator body 110 will typically occur.

In Figure 4, the aperture sub-segments 122a and 122b are now located further apart and also lower down the face 180 of the multi-mode resonator body 110. The horizontal component of the H-field, as designated by the H-field arrows 160, is now smaller (the vertical component, in contrast, now being larger) and consequently a reduced amount of H-field coupling to the Z mode will occur. Conversely, however, if the aperture sub-segments 122a and 122b were kept in the same locations on the face 180 of the resonator body 110, as shown in Figure 4, but each, individually, was rotated through 90 degrees, they would then typically provide a strong coupling magnitude to the Y-mode, from the H-field present immediately in front of the face 180 of the resonator body 110, although the couplings would typically be of opposing signs, due to the opposing field directions at the locations of aperture sub-segments 122a and 122b, and may therefore largely or entirely cancel each other out.

Note that whilst two separate aperture sub-segments are shown in both Figure 3 and Figure 4, the same arguments would hold true for a single aperture, for example aperture portion 122 in Figure 2; aperture portion 122 may be thought of as a long 'slot' encompassing both of the short 'slots' 122a and 122b of Figure 3. The main difference, from a coupling perspective, between the use of a single aperture portion,

122 and two aperture sub-segments, 122a and 122b, is that a greater degree of E-field coupling would typically be achieved using the single aperture portion 122 than would be achieved with the two aperture sub-segments 122a and 122b, assuming that the total length and the total aperture area occupied by the aperture sub-segments 122a and 122b is less than the total length and the total aperture area, respectively, of aperture portion 122. This increased degree of E-field coupling arises due to the increased useable area of the aperture portion and also from the stronger E field which is present closer to the centre of the face and which would typically be coupled by the central section of aperture portion 122. Such a large amount of E-field coupling is often undesirable, particularly when added to the E-field coupling which can arise from a similar pair of aperture sub-segments arranged vertically, to couple primarily to the Y-mode, such as apertures 312a and 312b in Figure 10(a), which will be discussed on more detail below.

With regard to the degree of E-field coupling which may be achieved using one or more aperture portions or aperture sub-segments, there are a range of factors which influence this. These include, but are not limited to:

1. Placement of the coupling aperture in a region where the E-field strength is highest, based upon the E-field present immediately adjacent to the face 180 of the resonator, but outside of the resonator body 110. In this case, the E-field coupling will typically be strongest close to, or at, the centre of the face 180 of the resonator body 110.

2. The provision of a large cross-sectional area for the coupling aperture 120, with an extension in both horizontal and vertical directions which corresponds to the shape of the E-field intensity present immediately adjacent to the face 180 of the resonator body 110. For example, a circular or a square aperture, placed at the centre of the face 180 of the resonator body 110, when employing a single-mode input resonator 190, as shown in Figure 6, would typically result in a large amount of E-field coupling taking place into the resonator body 110.

It is worth emphasising the point that an almost analogous situation exists, regarding aperture positioning and its impact upon coupling strength, for the E-field as has been

discussed (above) for the H-field. In the case of the example architecture shown in Figure 6, when considering the H-field, positioning the aperture(s) close to the edge of the face of the slab typically leads to a maximum level of coupling being achieved, assuming that the sub-apertures 121 and 122 are oriented appropriately to match the desired field direction at that location. In the case of the E-field, positioning the one or more apertures close to the centre of the face 180 of the multi-mode resonator body 110, leads to a maximum level of coupling. In this case, the orientation of the one or more apertures is largely unimportant. The shape of the aperture is now of greater relevance, with a circular shape typically providing a maximum amount of coupling relative to the area occupied by the coupling aperture, whilst removing the minimum amount of metallisation and hence having the minimum impact upon resistive losses in the filter.

Figure 5 illustrates a specific example in order to highlight the general principle of the invention. Figures 5(a) to (d) show an example coupling aperture arrangement consisting of four horizontally-oriented, narrow, apertures 511a, 511b, 512a, 512b and a single circular aperture 520 at the centre of the input face 180 of the multi-mode resonator. Figure 5(a) illustrates the field distribution which is assumed to exist outside of, but immediately adjacent to, the input face 180 of the multi-mode resonator. This field distribution is of a form which can exist within a single-mode input resonator, as previously discussed. In Figure 5(a), the H-field is shown by means of the solid lines, with arrowheads, 160, roughly circulating in a clockwise direction. Likewise, the E-field is shown by means of the small crosses – these are used to indicate that the E-field is directed roughly perpendicular to the page, approximately heading into the page. It should be noted that the density of the crosses is greater at the centre of the face 180 of the resonator, than it is toward the edges of the face. Likewise, the greater concentration of the H-field lines toward the outside edges of the face 180 and the lower concentration toward the centre of the face 180 show that the typical H-field distribution is such that a stronger H-field is usually present nearer to the edges and a lower H-field strength is usually present closer to the centre.

Figures 5(b) to (d) now show the field patterns existing immediately inside of the multi-mode resonator, in other words, immediately adjacent to the inside of the input

face 180 of that resonator, for the three modes which can exist in a cube-shaped resonator, if such a resonator is excited appropriately. Figure 5(b) shows a typical field pattern for the X-mode within the multi-mode resonator, based upon the excitation shown in Figure 5(a). It can be seen that the X-mode field pattern is similar to that of the excitation field pattern shown in Figure 5(a). The E-field of the X-mode is directed away from the input coupling apertures 511a, 511b, 512a, 512b in a direction roughly heading into the page. This is the x-direction, as indicated by the axes also shown in this figure.

Figure 5(c) shows a typical field pattern for the Y-mode within the multi-mode resonator. It can be seen that the Y-mode field pattern differs substantially from that of the excitation field pattern shown in Figure 5(a), for both the E and H-field components. The E-field of the Y-mode on this face is very small. The E-field of the Y-mode in the centre of the multi-mode resonator is large and propagates from left to right, in the Y-direction as indicated by the axes also shown in this figure. The H-field is shown as propagating from bottom to the top of the diagram, using the solid arrows.

Finally, Figure 5(d) shows a typical field pattern for the Z-mode within the multi-mode resonator. It can be seen that the Z-mode field pattern also differs substantially from that of the excitation field pattern shown in Figure 5(a), for both the E and H-field components. The E-field of the Z-mode, propagates from the bottom to the top of the diagram, in the Z-direction as indicated by the axes also shown in this figure, however as it is typically small, or zero, at the faces of the multi-mode resonator, it is not shown in this diagram; it would exist as described above, at the centre of the multi-mode resonator. The H-field is shown as propagating from left to right, using the solid arrows. It should be noted that the absolute directions of the E and H-fields are shown for illustrative purposes and field patterns oriented in the opposite directions to those shown are also possible.

Based upon the example field patterns shown in Figure 5, it is possible to provide an approximate indication of the relative coupling strengths which could, typically, be achieved, with the coupling aperture arrangement shown in this figure. Such an indicative summary is provided in Table 1, below. Specifically, this shows the

coupling which may be achieved when using only narrow, horizontally-oriented coupling apertures (or 'slots'), plus a central, circular, coupling aperture. In a typical, triple-mode filter, for example, it would be normal to also include vertically-oriented coupling apertures, to provide strong H-field coupling to the Y-mode; when using horizontal apertures, no vertical apertures, and assuming that any central aperture is perfectly centred and perfectly symmetrical, then minimal or no Y-mode coupling would typically occur.

Table 1 assumes that a single-mode cuboidal resonator, with a substantially square cross-section, is used to excite, by means of apertures located in its substantially square face, a cubic multi-mode resonator; both resonators having the aperture pattern shown in Figures 5(a) to (d) on their interfacing surfaces. With such an arrangement, and a suitable excitation device for the single-mode cuboidal input resonator, for example a probe, then field patterns similar to those shown in Figures 5(a) to (e) could be expected.

| | | | **Single-mode Resonator** | |
|---|---|---|---|---|
| | | | *X-mode* | |
| | **Resonator Mode** | **Aperture (see Figure 5)** | **E-field coupling** | **H-field coupling** |
| **Multi-mode Resonator** | *X-mode* | Apertures 511a & 511b | Weak (+) | Strong (-) |
| | | Apertures 512a & 512b | Weak (+) | Strong (-) |
| | | Aperture 520 | Strong (+) | Weak (-) |
| | *Y-mode* | Apertures 511a & 511b | 0 | 0 |
| | | Apertures 512a & 512b | 0 | 0 |
| | | Aperture 520 | 0 | 0 |
| | *Z-mode* | Apertures 511a & 511b | 0 | Strong (-) |
| | | Apertures 512a & 512b | 0 | Strong (+) |
| | | Aperture 520 | 0 | 0 |

Table 1

Table 1 may be interpreted as follows. The first resonator, in this case a single-mode input resonator, will typically only resonate in its X-mode, when fed with a probe, for

example. This single (X) mode will couple to the multiple modes which can be supported by the multi-mode resonator, by means of both its E and H fields, as highlighted by the vertical columns of Table 1. The coupling apertures are numbered according to the scheme shown in Figure 5(a), so apertures 511a and 511b, for example, are the upper two apertures in that figure. Taking these as an example, it can be seen, from Table 1, that the E-field present in the input single-mode resonator can weakly couple, with a 'positive' coupling, to the X-mode of the multi-mode resonator via apertures 511a and 511b. Likewise the H-field present in the input single-mode resonator can strongly couple, with a 'negative' coupling, to the X-mode of the multi-mode resonator via apertures 511a and 511b. The overall resultant coupling from the weak 'positive' coupling, resulting from the E-field present in the single-mode resonator, and the strong 'negative' coupling, resulting from the H-field present in the single-mode resonator, is a fairly strong negative coupling, based upon the two coupling apertures 511a and 511b only. Further contributions to the X-mode present in the multi-mode resonator will also result from apertures 512a and 512b and also the central aperture 520. Apertures 512a and 512b will, in effect, further strengthen the 'negative' signed coupling arising via from apertures 511a and 511b, however aperture 520 will counter-act this with the addition of strong 'positive' coupling. The resultant overall coupling to the X-mode will therefore depend upon how strong this positive coupling from aperture 520 is designed to be. If no central coupling aperture 520 is present, or this aperture is small, then the H-field coupling via apertures 511a, 511b, 512a and 512b will dominate; if, on the other hand, aperture 520 is large, then it could dominate the coupling to the X-mode. The final outcome is a matter of design choice, depending upon the particular filter specification to be achieved.

In the same manner, considering now the Z-mode within the multi-mode resonator, apertures 511a and 511b will generate strong negative coupling to this mode and apertures 512a and 512b will generate strong positive coupling to this mode. As drawn in Figure 5(a), where roughly equally-sized apertures are shown, these contributions may therefore roughly cancel each other out and only a weak or zero coupling to the Z-mode is likely to occur. In a typical practical design, one or more apertures would typically be reduced in size relative to the remainder, or one or more apertures may be eliminated entirely, in order to ensure some resultant coupling takes

place. So, for example, apertures 512a and 512b may be made smaller than apertures 511a and 511b, such that their coupling contribution is weakened, thereby allowing the coupling contribution from apertures 511a and 511b to dominate.

It is worth noting that the zero ("0") entries shown in Table 1 are illustrative of the fact that very minimal levels of coupling are likely to result, from the relevant combination of circumstances which gives rise to that particular entry; a zero ("0") entry does not necessarily imply that no excitation whatsoever will occur to that mode, by the relevant combination of circumstances which gives rise to that particular zero entry.

As has already been described, briefly, above, Figure 6 illustrates the addition of an input single-mode resonator 190 and an output single mode resonator 200 to the multi-mode resonator 110. The input single mode resonator 190 is typically attached to the front face 180 of the multi-mode resonator 110. The output single mode resonator 200 is typically attached to the rear face 230 of the multi-mode resonator 110. The input single mode resonator 190 and the output single mode resonator 200 are typically formed from a dielectric material. The dielectric material used may be the same dielectric material as is used to fabricate the multi-mode resonator body 110 or it may be a different dielectric material. The dielectric material used to fabricate the input single mode resonator 190 may be a different dielectric material to that used to fabricate the output single mode resonator 200. Both the input single mode resonator 190 and the output single mode resonator 200 are typically substantially coated in a metallisation layer, except for the aperture areas 120 and 130, respectively, over which the metallisation is removed or within which metallisation was not placed during the metallisation process. Figure 6 shows clearly, by means of cross-hatching, the area over which the metallisation 150 on the input face 180 of the multi-mode resonator body 110 extends and the area of the aperture 120, over which the metallisation is absent. Note that the remainder of the metallisation, which is typically applied to the remaining surfaces of the multi-mode resonator body 110, the surfaces of the input resonator 190 and the surfaces of the output resonator 200, is omitted from Figure 6, for clarity. The only exception to this is that metallisation 210 is shown on the surface of the output face 230 of the of the multi-mode resonator body

110, again by means of cross-hatching. It also shows the area of the aperture 130, over which the metallisation is absent, by an absence of cross hatching.

One purpose of the addition of single-mode resonators 190, 200, to the input and output faces 180, 230, of the triple-mode resonator body 110, is to contain the electromagnetic fields, for example H-field 160 and E-field 170, shown in Figure 2 for the input single mode resonator 190, which can then be coupled into the multi-mode resonator body 110, or which have been extracted from the multi-mode resonator body 110, in the case of the output single mode resonator 200.

The single-mode resonators 190, 200 may be supplied with a radio frequency signal or may have a radio frequency signal extracted from them, in a variety of ways, which are not shown in Figure 6, however one example architecture and method will be described later, with reference to Figure 13. The means by which radio frequency signals may be supplied or extracted include, but are not limited to: probes either touching the outer-most surface or penetrating the outer-most surface 240, 250 in Figure 6 of the input single-mode resonator 190 or the output single-mode resonator 200, respectively, single or multiple patches or patch antennas located in a suitable position or positions to provide the required electromagnetic field or fields to, or extract the required electromagnetic field or fields from, the single-mode resonators 190, 200, and either single or multiple conductive loops, again located in a suitable position or positions to provide the required electromagnetic field or fields to, or extract the required electromagnetic field or fields from, the single-mode resonators 190, 200.

The input and output single-mode resonators 190, 200 are also substantially covered in a metallic coating, in the same manner as the multi-mode resonator body 110, and also have apertures, within which substantially no metallisation is present, which typically correspond, in both size and location, to the apertures in the coating on the multi-mode resonator body 110. The input and output single-mode resonators 190, 200 are in direct or indirect electrical contact with, and typically also mechanically attached to, the multi-mode resonator body 110 at the locations shown in Figure 6 – that is to say that the metallisation layers on the outside of the single-mode and multi-mode resonators are typically electrically connected together across substantially all of

their common surface areas. Such a connection could be made by soldering, for example, although many other electrically-conductive bonding options exist.

The apertures 120, 130 in both the single and adjacent multi-mode resonators are, typically, substantially identical in shape, size and position on the relevant face of the resonator, such that they form, in essence, a single aperture, with a shape substantially identical to either of the apertures present on the relevant faces of the resonators, when the resonators are bonded together at those relevant faces. It is, however, possible to apply metallisation to only a single surface, either the output face of the input single-mode resonator or the input face of the multi-mode resonator, with the aperture or apertures incorporated into this single metallisation layer and then to bond this metallised surface to an adjacent resonator, which could have, as its bonding face, an un-metallised surface, with the remainder of that resonator being metallised. Care needs to be taken with this method of construction, however, to ensure that the bonding material, for example glue, is substantially of a uniform thickness. A separate electrical connection, between the metallisation on the two resonators is also, typically, required, for example at the top, the bottom and on both sides of both the input and output single-mode resonators 190, 200 and the multi-mode resonator body 110, to form, in effect, a continuous metallisation surrounding the whole filter structure, excluding the input and output connectors, probes or apertures.

Note that the term 'substantially identical', used above, is intended to include the case where one aperture is deliberately made slightly larger than an adjoining (facing) aperture, in order to simplify the alignment of the two apertures and thereby avoid mis-alignment problems between the two apertures.

Figure 7 shows the coupling arrangement of Figure 1, with the addition of arrows 610 indicating an example flow of current in the metallisation (not shown), located on the front face 180 of the multi-mode resonator 110, which could be anticipated, based upon the shape, size and location shown for the coupling aperture 120. It can be seen that the current flow 610 is generally directed from the central region to the outer Edges, of the front face 180 of the multi-mode resonator 110. Whilst this is clearly straightforward for the current flows heading downwards toward the bottom Edge and also those heading from left-to-right, toward the right-hand Edge, it is not so easy for

the currents needing to flow to the other two edges, owing to the presence of the aperture, which is formed by an absence of metallisation, thus impeding the flow of current. It can be seen from the current flows 600 extending around the ends of the coupling aperture 120 in Figure 7 that these currents tend to bunch together, thereby attempting to fit a comparatively large current through a comparatively narrow gap formed from the metallisation. The resistivity of the metallisation means that much greater resistive losses are likely to occur in this region than will typically occur from the largely unimpeded current flows indicated by the main body of the current arrows 610 which flow to the lower Edge and the right-hand Edge of the front face 180 of the multi-mode resonator 110.

This bunching of the currents is often referred to as 'current crowding' and leads to increased resistive losses occurring in the filter, as just described. These increased losses are undesirable and therefore it is advantageous to adopt a different form of aperture structure and layout, in order to achieve both strong coupling to all modes, within the multi-mode resonator, and also a low insertion loss for the resultant filter.

Figure 8 shows a multi-aperture structure according to one embodiment of the present invention. Only the front face 180 of the multi-mode resonator is shown in this figure and the metallisation is omitted, for clarity – only the outlines of the apertures 721a, 721b and 721c are shown. It can be seen from this figure that the basic right-angle aperture 120 of Figure 1 and Figure 7 has been, in effect, broken up into three separate aperture sub-segments, representing the corner section 721a, the tip of the horizontal section 721b and the tip of the vertical section 721c. The basic aperture configuration is also a mirror image, based upon a vertically-oriented mirror, of the one shown in Figure 1 and Figure 7; this change is only incorporated to show that the orientation of this aperture configuration is of secondary concern, relative to the basic shape and its position on the front face 180 in relation to the centre and Edges of that face 180 of the multi-mode resonator.

The original coupling aperture shape 120 has been replaced by a set of aperture sub-segments 721a, 721b, 721c, with three being used in this example, although more or fewer can also be used. These aperture sub-segments are separated by gaps containing metallisation, such as metallised gap 730 shown in dotted outline in Figure 8. These

metallised gaps may in fact be thought of as necks in the metallisation, arising between adjacent sub-segments. Note that the dotted outline is only shown to indicate the portion of aperture 120 which has now been replaced by metallisation; this metallisation is not typically distinct from the remainder of the metallisation on the front face of the multi-mode resonator. The aperture sub-segments 721a, 721b, 721c are typically formed by etching or a similar process, which results in metallisation either being deposited in the areas where it is required and withheld from the areas, such as the aperture sub-segments, where it is not required, or being etched away from the areas where it is not required, such as the aperture sub-segments, and being left largely untouched in the areas where it is required.

It can also be seen, from Figure 8, that the metallised gaps, such as metallised gap 730, appearing between the aperture sub-segments, such as aperture sub-segments 721a and 721b, allow the current to flow from the centre of the face 180 to the Edges, virtually unimpeded in any direction. This greatly improved current flow typically leads to a much reduced occurrence of the current-crowding problem described above and consequently results in an improved filter insertion loss for the complete multi-mode filter.

The aperture sub-segments shown in Figure 8 are, in effect, generally concentrated in the corners of the coupling face of the resonator, in other words, the majority of their cross-sectional area is toward the corners, rather than the centre, of the face 180 of the multi-mode resonator. In this location they will typically have a minimal detrimental effect on the current flowing within the metallisation, as has already been discussed, however they will still typically provide a sufficient coupling area over which to facilitate useful coupling to the H-fields flowing immediately adjacent to, for example, the face 180 of the multi-mode resonator. Such H-fields could be contained within an input or an output single-mode resonator (190, 200 in Figure 13), which may, in turn, be coupled to the outside world by means of a probe (1200 in Figure 13), for example.

The aim of the placement of the metallised gaps (for example, 730 in Figure 8) within the coupling aperture structure is therefore to minimise current crowding, whilst simultaneously achieving a given (required) amount of H-field coupling. The gaps are

typically placed in locations suitable for allowing the current to pass freely, so far as is practicable; in other words, locations where the current would ordinarily pass, if there were no apertures present in the metallisation. Placing gaps at these locations (or, conversely, not placing apertures in these locations) therefore minimises the disturbance to the current and hence minimises both mode rotation and filter losses.

Whilst the above discussion has concentrated on the apertures and sub-apertures appearing on the front face 180 of a single multi-mode resonator, the same arguments and the same coupling aperture arrangement may be used on any of the coupling faces of either the multi-mode resonator 110, any prior or subsequent multi-mode resonators, or any single-mode resonators used for input coupling, output coupling or multi-mode resonator to multi-mode resonator coupling (see, for example, the structure shown in Figure 15). The same benefits will apply in any of these locations and applications.

Figure 9 shows an example of a coupling aperture arrangement which may be capable of providing an increased amount of coupling to one or more of the modes in the multi-mode resonator, whilst still having a minimal impact upon the resistive losses present in the metallisation. In this figure, the coupling aperture sub-segments 821a, 821b, 821c, have been expanded or 'fattened' in terms of the aperture width, but not in terms of aperture length, in order to increase the area of the apertures; this 'fattening' of the apertures, when compared with those shown in Figure 8, is highlighted by showing the original shapes 721a, 721b, 721c, as dotted outlines, superimposed on the new apertures 821a, 821b, 821c. It is evident from Figure 9 that essentially no increase in current crowding and hence essentially no increase in resistive losses, should result from the increase in coupling area. By this means, it is typically possible to control the degree of coupling achieved to the modes within the multi-mode resonator, without adversely impacting the insertion loss of the filter.

Figure 10 shows a non-exhaustive range of alternative aperture shapes, according to the present invention, which could be used for either input coupling to the multi-mode resonator 110, for output coupling from the multi-mode resonator 110 or for coupling between multi-mode resonators, in the event that two or more are used in a particular design, for example to meet a particularly demanding filter specification. The

alternatives shown in Figure 10 are: (a) four separate aperture sub-segments, (b) three aperture sub-segments, forming a 'broken right-angle', (c) three aperture sub-segments comprising: a small cross, plus two, orthogonal, slots, (d) a 'broken cross' shaped aperture formed from four separate sub-segments, (e) four corner-shaped apertures. These alternative aperture shapes all operate using the same principles as those described above, with varying relative degrees of coupling to the various modes.

Figures 10(a), (b) and (c) will now be discussed together, in more detail, since they are essentially all variants of the same theme. Figure 10(a) shows four separate aperture sub-segments in the form of horizontally-oriented and vertically-oriented 'slots'; these can be thought of as being operationally similar to the aperture coupling structure of Figure 1(b), but with some parts of the aperture 'missing'; in other words parts of the metallisation on the face 180 of the multi-mode resonator 110 which had been removed to create the aperture 120, for example, in Figure 1 are now present, in Figure 10(a), thereby breaking up the original aperture shape into smaller aperture sub-segments 311a, 311b, 312a, 312b and entirely omitting some parts, such as the upper left-hand corner of input coupling aperture 120 in Figure 1(a). The aperture form shown in Figure 10(a) will operate in a similar manner, however, to that of Figure 1(b), although it will typically have a somewhat lower degree of E-field coupling to the X-mode, due to the smaller total area occupied by the slots and their location far from the centre of the face 180 of the resonator. The degree of H-field coupling to the Y and Z modes can also decrease, however this does not, typically, occur to the same degree as that of the E-field coupling to the X-mode and this is a significant benefit of this aperture arrangement. It is therefore possible to utilise the aperture arrangement of Figure 10(a) to provide strong H-field coupling to the Y and Z modes, together with strong positive H-field coupling to the X-mode, whilst minimising the amount of negative E-field coupling to the X-mode, which acts to partially cancel the positive coupling to the X-mode arising from the H-field. Minimising the degree of cancellation which occurs in coupling to the X-mode not only enables an appropriate degree of X-mode excitation to be achieved in the multi-mode resonator, to enable it, in conjunction with Y and Z-mode excitation, to meet many filter specifications appropriate in the mobile communications industry, it also helps to minimise the insertion loss of the resulting filter, in its pass-band.

Figure 10(b) now shows the situation in which two of the aperture sub-segments in Figure 10(a) have been moved slightly and merged to form a 'corner' shape 321a. Again, the operation of this overall aperture structure, comprising 321a, 321b and 321c, is similar to that of aperture 120 in Figure 1, but again with typically a lower level of E-field and H-field coupling to all modes than would be obtained from the input coupling aperture 120 shown in Figure 1(b). It would also typically exhibit a different level of coupling to at least some of the various modes, supported within the multi-mode resonator 110, than would be the case with the aperture configuration shown in Figure 10(a), although this difference would usually be less pronounced than that between the aperture shapes and sizes shown in Figure 1 and Figure 10(a). For example, it is likely that there would exist a lower level of E-field coupling to the X mode when using the aperture configuration shown in Figure 10(b), when compared to that shown in Figure 10(a), due to the reduction in the total cross-sectional area occupied by the coupling aperture sub-segments 321a, 321b, 321c on the face 180 of the multi-mode resonator 110, relative to that of the aperture configuration shown in Figure 10(a), thereby reducing the available area through which the E-field can propagate.

Figure 10(c) shows, in effect, a further shift of the apertures of Figure 10(a), which has now turned the 'corner' 321a in Figure 10(b) into a small cross 331a in Figure 10(c). This will typically decrease the H-field coupling to the Y and Z modes, relative to that obtained when using the coupling aperture arrangement shown in Figure 10(a), largely due to the fact that the apertures have moved closer to the centre of the face, where the H-fields are weaker.

Whilst the discussion of aperture-based coupling, above, has concentrated on specific, predominantly rectilinear, aperture shapes, there are many other possible aperture shapes, which would also obey similar principles of operation to those described. Examples of suitable aperture shapes include, but are not limited to: circles, squares, ellipses, triangles, regular polygons, irregular polygons and amorphous shapes. The key principles are: i) to enable coupling to, predominantly, the X-mode within a multi-mode resonator, by means of an E-field existing adjacent to, but outside of, the said multi-mode resonator, where the degree of coupling obtained is based upon the aperture area or areas and the aperture location or locations on the face of the said

multi-mode resonator; and ii) to enable coupling to the Y and Z modes within a multi-mode resonator, by means of an H-field existing adjacent to, but outside of, the said multi-mode resonator, where the degree of coupling obtained is based upon the aperture area or areas and the aperture location or locations on the face of the said multi-mode resonator, wherein the mode (Y or Z) to be predominantly coupled to is based upon the horizontal (for the Z-mode) or vertical (for the Y-mode) extent of the coupling aperture or apertures and its (or their) locations relative to the centre of the face of the said multi-mode resonator.

A common application for filtering devices is to connect a transmitter and a receiver to a common antenna, and an example of this will now be described with reference to Figure 11(a). In this example, a transmitter 951 is coupled via a filter 900A to the antenna 950, which is further connected via a second filter 900B to a receiver 952. Filters 900A and 900B could be formed, for example, utilising the resonator arrangement shown in Figure 6, with the addition of a suitable arrangement to couple energy into input resonator 190 and a second arrangement to couple energy from output resonator 200. An example of a suitable arrangement for either or both of coupling energy into input resonator 190 and coupling energy from output resonator 200 would be the use of a probe, in each case and this approach is described in more detail below, in conjunction with Figure 13.

In use, the arrangement shown in Figure 11(a) allows transmit power to pass from the transmitter 951 to the antenna 950 with minimal loss and to prevent the power from passing to the receiver 952. Additionally, the received signal passes from the antenna 950 to the receiver 952 with minimal loss.

An example of the frequency response of the filter is as shown in Figure 11(b). In this example, the receive band (solid line) is at lower frequencies, with zeros adjacent the receive band on the high frequency side, whilst the transmit band (dotted line) is on the high frequency side, with zeros on the lower frequency side, to provide a high attenuation region coincident with the receive band. It will be appreciated from this that minimal signal will be passed between bands. It will be appreciated that other arrangements could be used, such as to have a receive pass band at a higher frequency than the transmit pass band.

It will be appreciated that the filters 900A, 900B can be implemented in any suitable manner. In one example, each filter 900A and 900B includes two resonator bodies provided in series, with the four resonator bodies mounted on a common substrate, as will now be described with reference to Figure 12.

In this example, multiple resonator bodies 1010A, 1010B, 1010C, 1010D can be provided on a common multi-layer substrate 1020, thereby providing transmit filter 900A formed from the resonator bodies 1010A, 1010B and a receive filter 900B formed from the resonator bodies 1010C, 1010D.

Accordingly, the above described arrangement provides a cascaded duplex filter arrangement. It will be appreciated however that alternative arrangements can be employed, such as connecting the antenna to a common resonator, and then coupling this to both the receive and transmit filters. This common resonator performs a similar function to the transmission line junction 960 shown in Figure 11(a).

Figure 13(a) illustrates the use of coupling probes 1200, 1210 to feed signals into the input single-mode resonator 190 and to extract signals from the output single-mode resonator 200. The structure shown is similar to that shown in Figure 6, however, in the case of Figure 13, the coupling aperture 120 has been replaced by three aperture sub-segments, 321a, 321b and 321c. These aperture sub-segments, together with their operation, have been previously described with reference to Figure 10(b). The output coupling aperture 130 of Figure 6 has, likewise been replaced by three sub-segments, only two of which can be seen in the perspective view shown in Figure 13(a); those being: aperture sub-segments 322a and 322b.

Figure 13(b) illustrates a side-view of the filter arrangement shown in Figure 13(a). The input coupling probe 1200 can be seen to penetrate significantly into the input single-mode resonator 190; likewise, the output coupling probe 1210 can be seen to penetrate significantly into the output single-mode resonator 200. The degree of probe penetration employed for either the input coupling probe 1200 or the output coupling probe 1210 is a design decision and depends upon the precise filter characteristics which are required in the application for which the filter is being designed. Penetration depths ranging from no penetration at all, where the probe just

touches the outer face of the input single-mode resonator 190, for example, to full penetration, where the probe extends to the front face of the multi-mode resonator 110, which may or may not be metallised, for example due to the location of the input coupling apertures 1220. An analogous situation exists at the output of the filter, for the penetration depth of the output coupling probe 1210 within the output single-mode resonator 200. Here, again, the output coupling apertures 1230 may be located centrally or peripherally, or both, on the output face 1250 of the multi-mode resonator 110, meaning that a fully-penetrating probe may or may not contact the metallisation surrounding the multi-mode resonator 110.

As has been discussed briefly above, the input single mode resonator 190 and the output single mode resonator 200 operate to transform the predominantly E-field generated by the input coupling probe 1200 from a largely E-field emission into an E and H-field structure, which can then be used, in turn, to simultaneously excite two or more of the modes of the multi-mode resonator 110. This situation is illustrated in Figure 14.

These are two key advantages to the use of single mode resonators, together with probes or another suitable field excitation mechanism, such as patches or loops, as a means for exciting or extracting energy from multiple modes simultaneously, in a multi-mode resonator based filter structure:

1. The addition of single-mode resonators enables an input signal connection mechanism or coupling structure which is, of itself, incapable of exciting multiple modes simultaneously (in this case, a probe), to be used to excite multiple modes simultaneously in a multi-mode resonator, without recourse to additional measures, such as the addition of defects to the multi-mode resonator.

2. The addition of single-mode resonators provides additional filtering to assist in, for example, removing out of band products or to improve the cut-off performance immediately adjacent to the wanted pass-band. In the case of two added single-mode resonators, one at the input to the system and one at the output, two single-mode filters are, in effect, added to the existing triple mode filter. These can significantly improve the overall filtering performance.

It is notable that Figure 13(a) (and also Figure 6) depicts input and output single-mode resonators, 190, 200, which are smaller, i.e. thinner, than the multi-mode resonator 110. This depiction is deliberate, since the thickness of the single-mode resonators is typically an important design parameter in achieving a good overall filter specification.

The input and output single-mode resonators will typically possess both wanted and unwanted resonances and it is important to place the one or more unwanted resonances at frequencies where they may be reduced or removed simply and with the introduction of minimal additional losses, in effecting their removal. One way to achieve this goal is to ensure that the thickness, or X-dimension as defined in Figure 13(a), of the input resonator, say, is designed such that the first two resonant modes of that resonator are arranged as follows: The first resonant mode is placed within the wanted pass-band of the overall filter; in this way it can provide additional, useful, filtering as discussed above. The second resonant mode is then, as a consequence of placing the first within the filter pass-band, typically located at the first harmonic of the pass-band, i.e. at double the pass-band frequency. Thus, for example, a filter with a pass-band centre frequency designed to be at 1.8GHz will have an unwanted resonance and hence an unwanted reduction in the stop-band attenuation, resulting from the input resonator, at approximately 3.6GHz. This unwanted resonance can then be reduced or removed by means of a separate, cascaded, filter, which could be in the form of a low-pass, a band-pass or a notch filter.

Note that an analogous situation to that described above, in respect of the input resonator, also exists for the output resonator and it, too, will therefore, typically, be thinner, i.e. smaller in the X-dimension, than will the multi-mode resonator and it may be of the same dimensions as the input resonator.

The above-discussed ability to provide a wide separation between the wanted and spurious resonances of both the input and output resonators is an advantage over alternative, conductive-track based coupling structures, designed to excite multiple modes simultaneously within a multi-mode resonator. In the case of conductive-track based coupling structures, it is generally not desirable to place the first resonant mode within the overall filter's pass-band, since the Q of this first resonant mode will be

relatively poor and consequently it will degrade some or all of the pass-band characteristics of the overall filter. It will not, as was the case with input or output resonant cavities, provide useful additional filtering, indeed quite the reverse will be the case. It is therefore typically necessary to place the first resonant mode of the track-based coupling structure below the filter pass-band and the second resonant mode will therefore typically appear above the pass--band. Whilst it is possible to reduce or remove these additional spurious resonances, by means of an additional band-pass filter, for example, such a filter would need to have good roll-off performance characteristics and would therefore, typically, introduce excessive, unwanted, losses in the overall filter's pass-band. It is one of the aims of the present invention to realise a low-loss, high-performance, filter and consequently such additional losses are generally unacceptable.

Figure 14(a) shows the situation in which an input coupling probe 1200 is directly inserted into a dielectric-filled, externally-metallised, cavity 110 which would ordinarily be capable of supporting multiple modes simultaneously, based upon its shape, dimensions and the material from which it is constructed. In this case, however, an input single-mode resonator is not used (the probe being directly inserted in to the multi-mode-capable cavity) and no defects are applied to the cavity, such as holes or corner-cuts being imposed upon the dielectric material. In other words, a cavity 110 which it is desired to be resonant in two or more modes and with a shape suitable to support such a diversity of modes is attempting to be directly excited by a probe 1200, without further assistance. In this case, the probe generates substantially an E-field; unsurprising since its primary characteristic is that of an E-field emitting device. This E-field will then excite a single mode in the main resonator – with the axes as defined in Figure 14(a), this is the X-mode. Without the use of additional defects in the main resonator, such as corners milled off the cuboidal resonator shape, additional, un-driven, probes or screws inserted into the resonator at carefully designed locations or some other means, it is not typically possible for the probe to excite significant (i.e. useful, from a high-performance filtering perspective) resonances in either of the other two modes, Y or Z. Note that in Figure 14(a), the E-field emission from the far end of the probe is shown in an indicative manner and is not intended to be an accurate representation of the precise E-field generated by the

probe. Note also that it is assumed that the resonator cavity 110 would be metallised on all surfaces, barring, possibly, a small area surrounding the input probe 1200, depending upon its design, although such metallisation is omitted from Figure 14(a), for clarity.

Figure 14(b) shows the situation in which an input coupling probe 1200 is now inserted into a single-mode dielectric resonator 190, which is in turn coupled to a multi-mode resonator 110 by some means; this means being apertures, in the case of Figure 14(b), although other possibilities exist, such as etched tracks, patches and other structures. Note that in this figure, as in Figure 14(a), only an input coupling mechanism is shown – a typical practical filter design would also require a separate output coupling mechanism, as shown, for example, in Figure 13.

Figure 14(b) illustrates, in detail, the primary fields, currents and excited modes present within the design, although not all fields are shown, to aid clarity. Note that the fields shown are representational only, and do not accurately convey the shape of the fields within the multi-mode resonator; this figure is intended to show the relative directions of the modes and not their shapes. For example, the E-fields present within the resonator will fall to a minimum and ideally, zero, at the metallised walls of the resonator, for the modes in which the E field is parallel to the wall. The single mode resonant cavity 190 takes the energy from the E-field generated by the input probe and this predominantly excites a single resonant mode within the cavity; with the arrangement shown, this would typically be the X-mode of the single-mode resonant cavity 190. This mode will typically, in turn, induce currents in the metallisation 1310 on the interface 1300 between the single and multi-mode resonators; these currents are shown by means of the dash-dot arrows in Figure 14(b). This process will also typically generate an H-field 160, which can circulate, as shown in Figure 14(b), and can have a greater intensity toward the outside of the resonator and a lower intensity closer to the centre. Finally, an E-field (not shown in Figure 14(b), although it is highlighted 170 in Figure 2), will typically be generated, which will generally be aligned parallel to the shorter edges of the single-mode resonator 190, in other words, in parallel with the extruded direction of the probe.

Figure 14(c) is a version of Figure 14(b) with the input resonator, probe and metallisation removed, to allow the field directions to be seen more easily. As above, the fields shown are representational only, and do not accurately convey the shape of the fields within the multi-mode resonator; this figure is intended to show the relative directions of the modes and not their shapes. For example, the E-fields present within the resonator will fall to a minimum and ideally, zero, at the metallised walls of the resonator, for the modes in which the E field is parallel to the wall.

From these currents and fields, all available fundamental modes of the multi-mode resonator 110 may be excited, simultaneously, as follows. The E-field can propagate through the aperture sub-sections 321a, 321b, 321c, in a direction perpendicular to the plane of the apertures, and will excite the X-mode within the main resonator. The horizontal component of the H-field 160 can be coupled by the upper, horizontally-aligned, parts of the coupling aperture sub-sections 321a and 321b and this will typically couple, predominantly, to the Z-mode in the multi-mode resonator. Finally, the vertical component of the H-field 160 can be coupled by the left-most, vertically-aligned, parts of the coupling apertures sub-sections 321a and 321c, and this will typically predominantly couple to the Y-mode in the multi-mode resonator 110. In addition to coupling to the Y and Z-modes, the H-field 160 will also, typically, couple to the X-mode in the multi-mode resonator 110, but generally in the opposite sense to the X-mode excitation resulting directly from the E-field. These two mechanisms for coupling to the X-mode, namely that arising from the E-field present in the input single-mode resonator 190 and that arising from the H-field present in the input single-mode resonator 190, can act in opposition to one another and the weaker coupling effect can, therefore, partially cancel the effect of the stronger coupling effect. It is the resultant of this cancellation process which largely determines the amount of the X-mode present in the multi-mode resonator 110.

In this manner, all supported modes in the multi-mode resonator 110 may be excited simultaneously by means of a single probe, with no defects typically being required to any of the resonators within the design.

Some filter specifications are particularly demanding, for example in terms of the steepness of their pass-band-to-stop-band roll-off characteristics and consequently a

single multi-mode resonator, even with the addition of its associated input and output single-mode resonators, and consequently their filtering characteristics, is not sufficient to meet the specified requirements. In such circumstances, an additional multi-mode resonator may be employed, within the cascade of resonators. This second multi-mode resonator may be made to the same design, shape and dimensions and be made of the same material, as the first multi-mode resonator, or it may be different in one or more of these areas. However it is configured or fabricated, it must able to extract energy from the prior element in the filter cascade and supply energy to the subsequent element in the filter cascade, with as lower level of losses as possible. Figure 15 illustrates one option for configuring such a filter: that of employing a further single-mode resonator 1470 located between the two multi-mode resonators 1450, 1460, in the centre of a filter cascade. The purpose of this further single-mode resonator 1470 is to facilitate coupling from a first multi-mode resonator to a second multi-mode resonator, in a simple and straightforward manner. The remainder of the filter is similar, in arrangement for Figure 13(a), having an input single-mode resonator 190, an output single-mode resonator 200, each fed by respective probes 1200, 1210 and each using coupling apertures 1410, 1440 to provide excitation to or extract energy from an adjacent multi-mode resonator 1450, 1460.

The operation of the filter is also similar to that of Figure 13(a), in particular regarding the use of the input and output probes, input and output single-mode resonators and their associated coupling apertures. These aspects will, therefore, not be described further. The main area of difference lies in the use of a further single-mode resonator 1470 to facilitate the coupling of multiple modes from a first multi-mode resonator 1450 to a second multi-mode resonator 1460. The process of coupling takes place, typically, as follows. The first multi-mode resonator 1450, whose multiple resonant modes have undergone excitation via the input apertures 1410, may have that energy largely extracted via coupling apertures 1420 in a similar manner as has already been described in relation to coupling aperture 130 of Figure 6. The energy contained in the multiple modes of the first multi-mode resonator 1450 will thereby largely pass into the single-mode resonator 1470, in the form of a single-mode excitation. This single-mode excitation can then largely excite multiple modes in a second multi-mode resonator 1460, via coupling apertures 1430. Again, the excitation mechanisms, in

this case, are similar to those described previously in relation to aperture 120 in Figure 6 and apertures 321a, 321b, 321c of Figure 14(b). Single-mode resonator 1470 is therefore acting as both an output single-mode resonator for the first multi-mode resonator 1450 and as an input single-mode resonator for the second multi-mode resonator 1460. Coupling from a first multi-mode resonator to a second multi-mode resonator may therefore be facilitated by the use of a single, single-mode resonator placed between the two. Likewise, by extension, multiple, multi-mode resonators may be coupled together by means of a single, single-mode resonator being placed between adjacent multi-mode resonators.

The use of intervening single-mode resonators, between multi-mode resonators, as just described, enables a high degree of control to be provided of the mode-to-mode coupling between the multi-mode resonators. This is more difficult to achieve with direct multi-mode resonator to multi-mode resonator coupling.

All of the examples shown and discussed so far have been in the form of linear cascades of dielectric resonators. It is not, however, essential that all embodiments of a multi-mode filter, according to the present invention, are arranged as a linear cascade. Multiple modes within a multi-mode resonator can typically be excited via any one of a number of faces, or any face, of the multi-mode resonator, by the provision of one or more suitably-designed apertures on that face or faces and the provision of a suitable electromagnetic field adjacent to the apertures, to provide the source of the excitation. As an example of an alternative arrangement, to illustrate this general principle, Figure 16 shows a three-resonator filter with input and output coupling resonators 190, 200, appearing on perpendicular faces of a multi-mode resonator 110. This is an analogous configuration to that shown earlier in Figure 13(a). An arrangement of resonators, such as that shown in Figure 16, may typically be advantageous in a duplexer application, since such an arrangement could allow the transmit and receive ports to be spatially separated to the maximum degree possible, for a given number of resonators employed within each of the transmit and receive filters.

Note that, as in Figure 13(a) most of the metallisation surrounding the resonators has been omitted in Figure 16, to enable the various coupling apertures and the basic

structure of the multi-resonator filter to be seen more clearly. A practical filter would typically feature metallisation substantially covering all faces of each of the resonators forming the filter, with metallisation removed or omitted to form the apertures.

The operation of the filter shown in Figure 16 is analogous to that of Figure 13a, although the precise design of the aperture shape or shapes, sizes, orientations or locations on the input face 2030 of the multi-mode resonator 110 may be different. An input signal, connected to input probe 1200, can excite one or more modes in input resonator 190. The one or more modes present in input resonator 190 may, in turn, excite multiple modes within the multi-mode resonator 110, via one or more of apertures 2021a, 2021b and 2021c. The multiple modes present within the multi-mode resonator 110 may be extracted, via one or more of apertures 2022a, 2022b and 2022c and thereby excite one or more modes within output resonator 200. Finally, signals may be extracted from output resonator 200 by means of a probe (not shown) which is located in close proximity to, touches or penetrates the output face 2050 of the output resonator 200.

The above described examples have focused on coupling to up to three modes. It will be appreciated this allows coupling to be to low order resonance modes of the resonator body. However, this is not essential, and additionally or alternatively coupling could be to higher order resonance modes of the resonator body.

Persons skilled in the art will appreciate that numerous variations and modifications will become apparent. All such variations and modifications which become apparent to persons skilled in the art are considered to fall within the spirit and scope of the invention broadly appearing before described.

## CLAIMS

1. A multi-mode cavity filter, comprising:

at least one dielectric resonator body incorporating a piece of dielectric material, the piece of dielectric material having a shape such that it can support at least a first resonant mode and at least a second resonant mode that is substantially degenerate with the first mode;

a layer of conductive material in contact with and covering the dielectric resonator body; and

a perforated zone providing apertures in the layer of conductive material for at least one of:

inputting signals to the dielectric resonator body, and

outputting signals from the dielectric resonator body;

2. wherein the perforated zone includes a first aperture adjacent a second aperture, the first and second apertures define between them a neck and the width of the neck along the axis is sufficient so that the neck does not substantially impede current flow through the layer.

3. A multi-mode cavity filter according to claim 2, wherein said axis is substantially parallel to a magnetic field of one of said modes or to a face of the body.

4. A multi-mode cavity filter according to claim 1, wherein the first aperture is primarily for coupling to one of said modes and the second aperture is primarily for coupling to another one of said modes.

5. A multi-mode cavity filter according to claim 1, wherein the first aperture is an elongate aperture that is elongated along a first axis parallel with a magnetic field of one of said modes and the second aperture is an elongate aperture that is elongated along a second axis parallel with a magnetic field of another of said modes.

6. A multi-mode cavity filter according to claim 1, wherein the first aperture is an elongate aperture that is elongated along a first axis substantially parallel to a surface of the body and the second aperture is an elongate aperture that is elongated along a second axis that is substantially perpendicular to the first axis.

7. A multi-mode cavity filter according to claim 1, wherein the first aperture is an elongate aperture that is elongated along a first axis non-parallel with, but not perpendicular to, a magnetic field of one of said modes and the second aperture is an elongate aperture that is elongated along a second axis non-parallel with, but not perpendicular to, a magnetic field of another of said modes.

8. A multi-mode cavity filter according to any one of claims 1 to 7, wherein:
the perforated zone extends over a face of said body;
at least one of the first and second apertures is located such that 80% of its area is in a strong magnetic coupling zone; and
the strong magnetic coupling zone is a part of the face that lies beyond a circle whose centre is a centroid of the face and whose radius is 50% of the radius of the largest circle having a centre at the centroid that can be fitted on the face.

9. A multi-mode cavity filter according to any one of claims 1 to 7, wherein:
the perforated zone extends over a face of said body;
at least one of the first and second apertures is located such that 80% of its area is in a strong magnetic coupling zone; and
the strong magnetic coupling zone is a part of the face that lies beyond a regular polygon:
whose centre is a centroid of the face;
whose area is 50% of area of the face; and
which fits on the face.

10. A multi-mode cavity filter, comprising:
at least one dielectric resonator body incorporating a piece of dielectric material, the piece of dielectric material having a shape such that it can support at least a

first resonant mode and at least a second resonant mode that is substantially degenerate with the first mode;

a layer of conductive material in contact with and covering the dielectric resonator body; and

a perforated zone providing apertures in the layer of conductive material for at least one of:

inputting signals to the dielectric resonator body, and

outputting signals from the dielectric resonator body;

wherein:

the perforated zone extends over a face of the body;

the face has at least four edges serving to define a perimeter of the face;

the apertures are arranged so that, for each edge, the apertures cover less than 50% of any path that runs parallel to that edge in a guard band on the face; and

the guard band is a part of the face that:

lies between the perimeter and a boundary on the face running parallel to the perimeter; and

has an area of 20% of the area of the face.

11. A multi-mode cavity filter according to any one of the preceding claims, wherein each of a plurality of said modes provides a respective individual pass band in the filter's frequency response, said individual pass bands merge into a continuous pass band in said frequency response and the continuous pass band spans a greater range of frequencies than the largest of said individual pass bands.

12. A multi-mode cavity filter according to any one of the preceding claims, wherein said body additionally supports at least a third resonant mode that is substantially degenerate with said first and second modes, said set further includes said third mode, and the first, second and third modes are mutually orthogonal.

13. A multi-mode cavity filter according to any one of the preceding claims, wherein the perforated zone comprises an aperture for coupling simultaneously to two of said modes.

14. A multi-mode cavity filter according to any one of the preceding claims, further comprising a first cavity resonator for coupling electric and magnetic fields into the multi-mode resonator via the perforated zone.

15. A multi-mode cavity filter according to claim 14, wherein the first cavity resonator is provided with a probe for feeding a signal into the first cavity resonator.

16. A multi-mode cavity filter according to any one of the preceding claims, further comprising a second cavity resonator for coupling electric and magnetic fields out of the multi-mode resonator via the perforated zone.

17. A multi-mode cavity filter according to claim 16, wherein the second cavity resonator is provided with a probe for extracting a signal from the second cavity resonator.

18. A multi-mode cavity filter according to any one of the preceding claims, wherein at least one of the first and second apertures is one of a slot or other straight sided shape, an amorphous shape, a curved shape and a symmetrical shape.

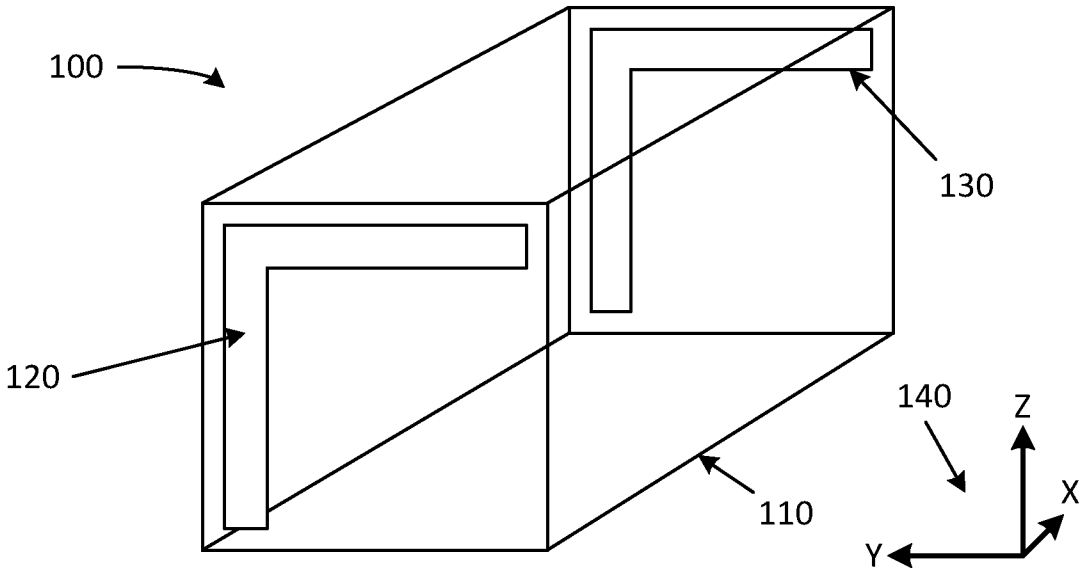



Figure 1 (a)

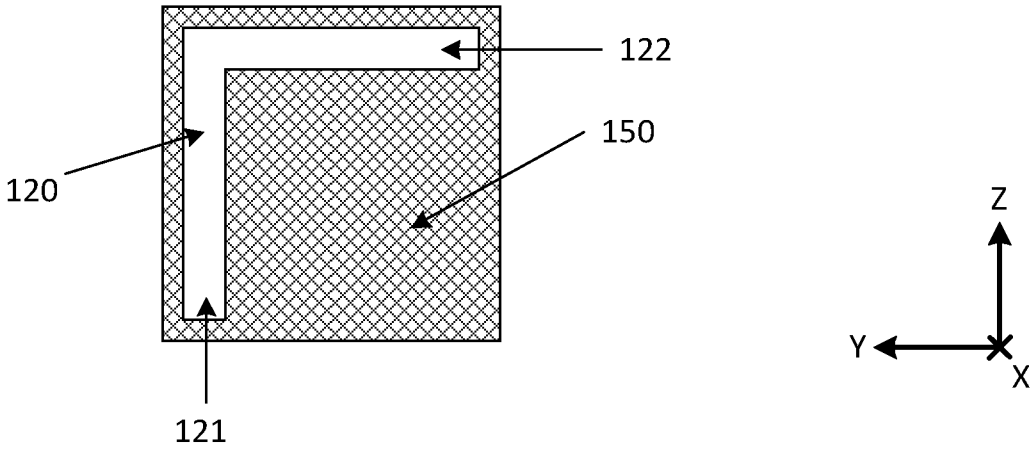



Figure 1 (b)

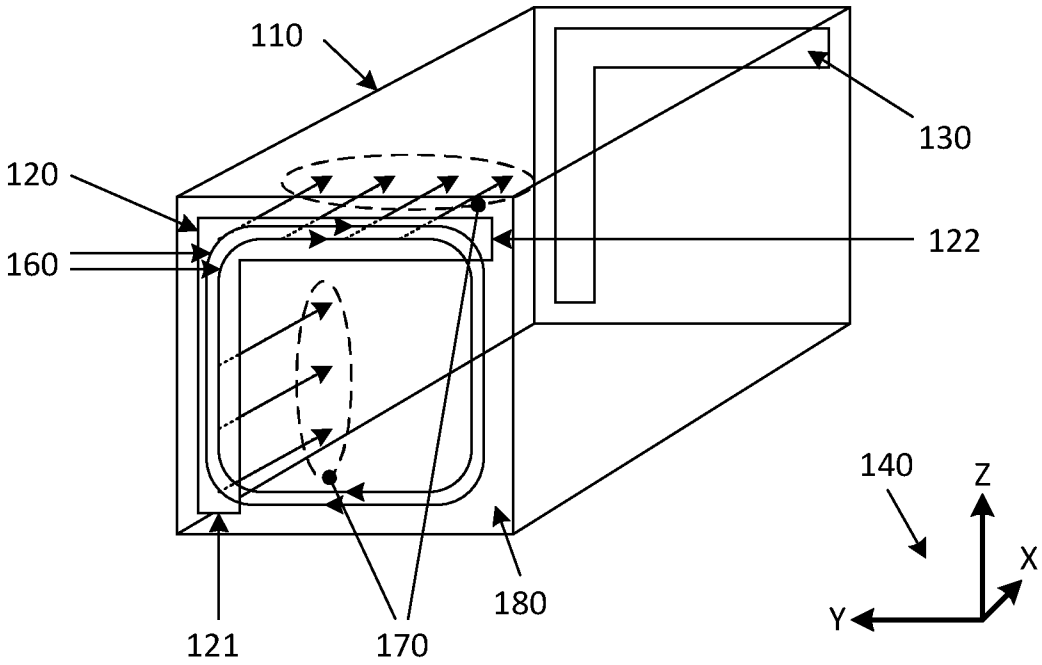



Figure 2

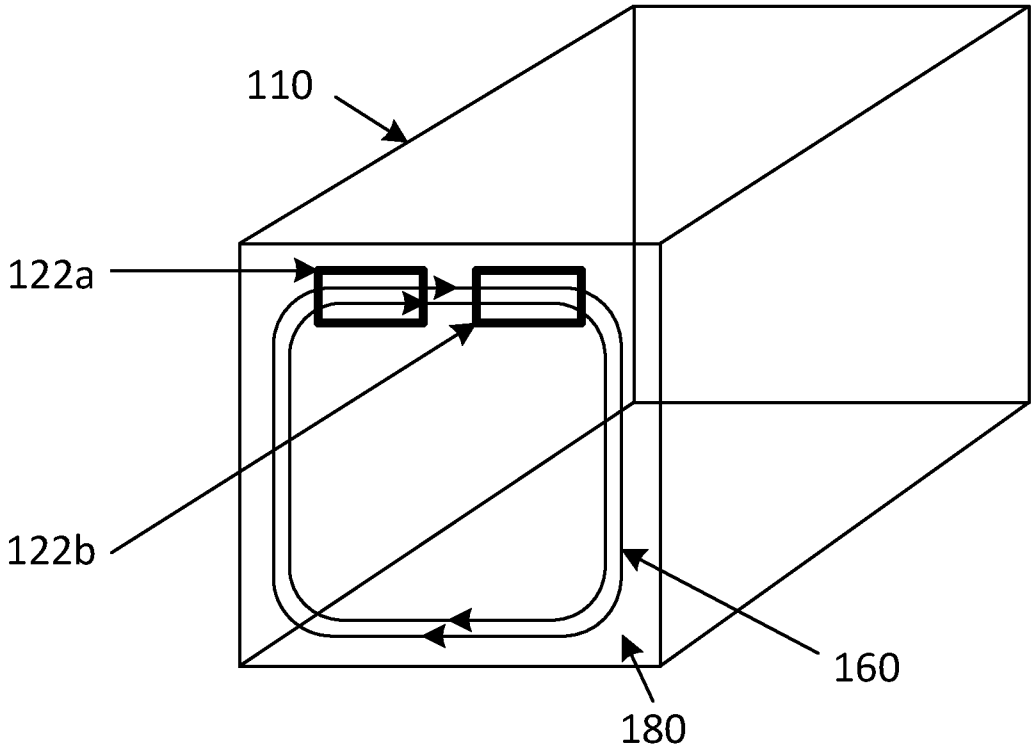



Figure 3

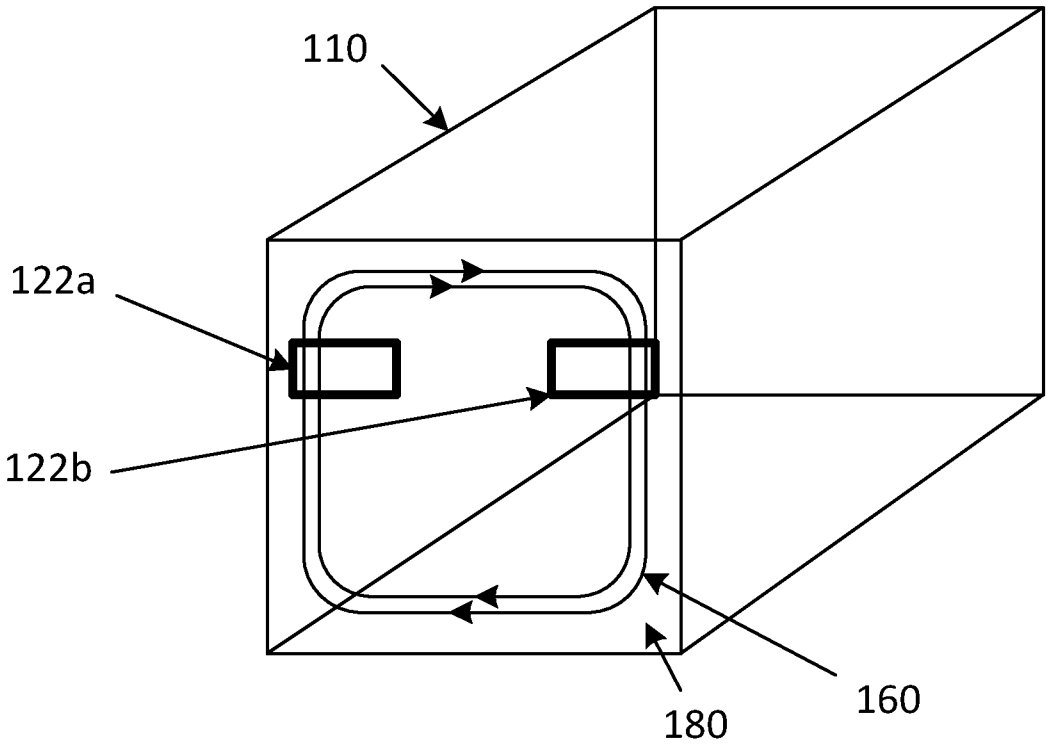



Figure 4

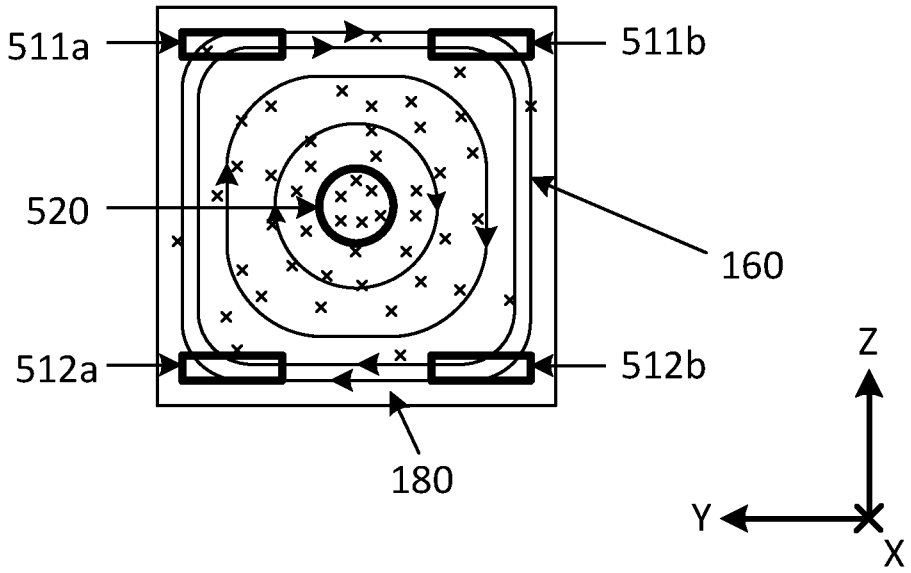



Figure 5 (a)

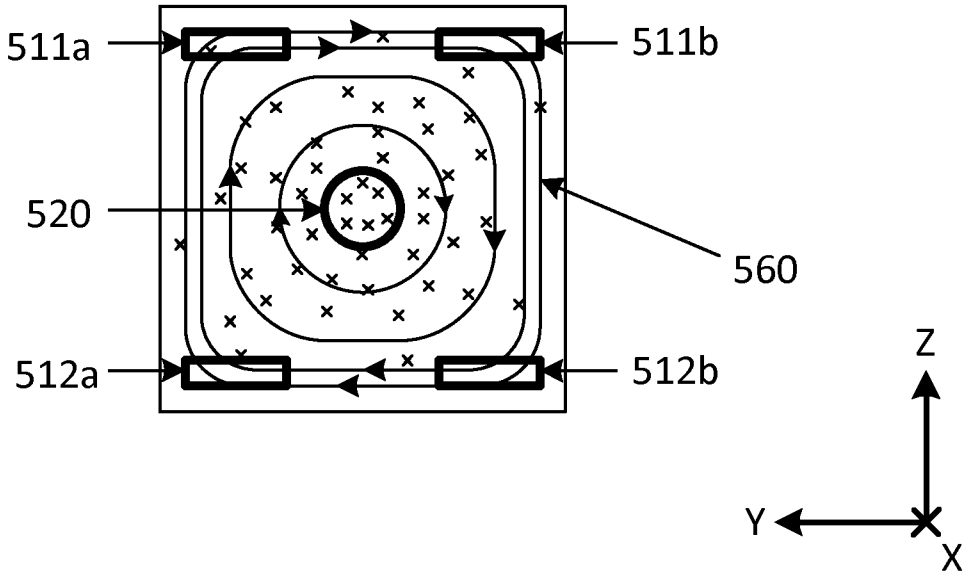



Figure 5 (b)

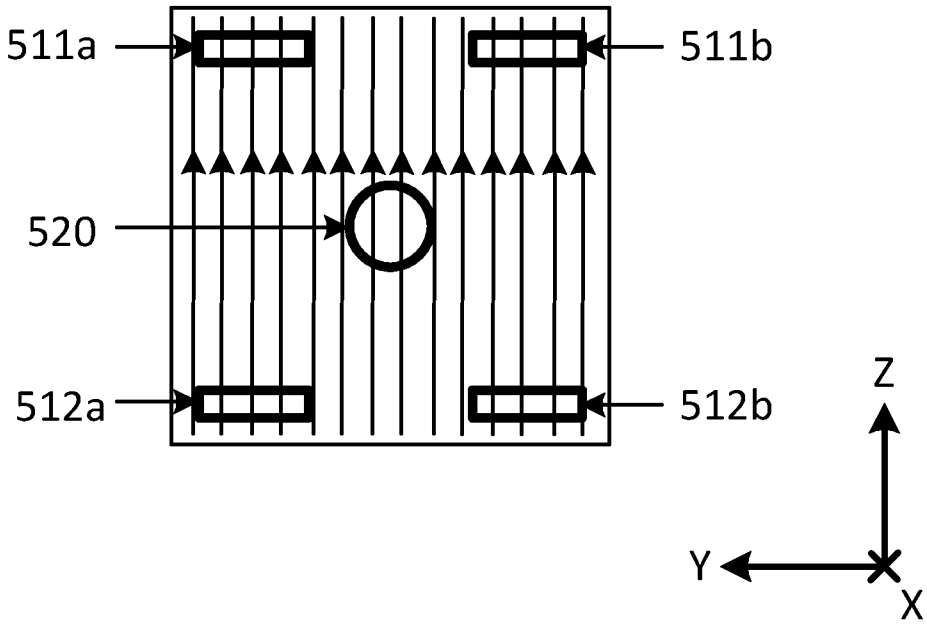



Figure 5 (c)

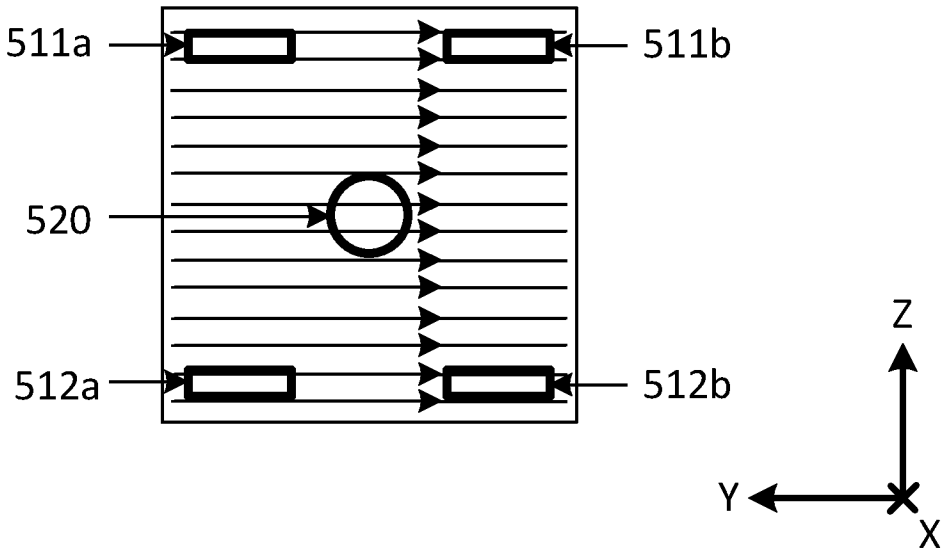



Figure 5 (d)

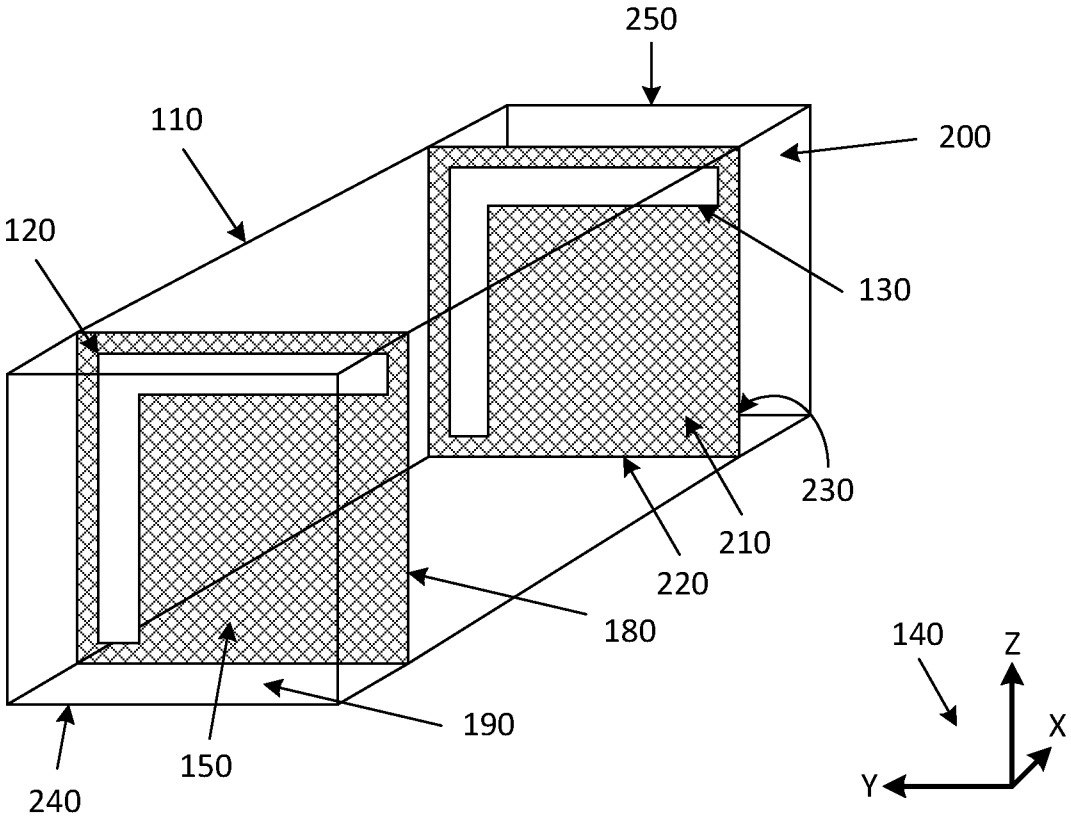



Figure 6

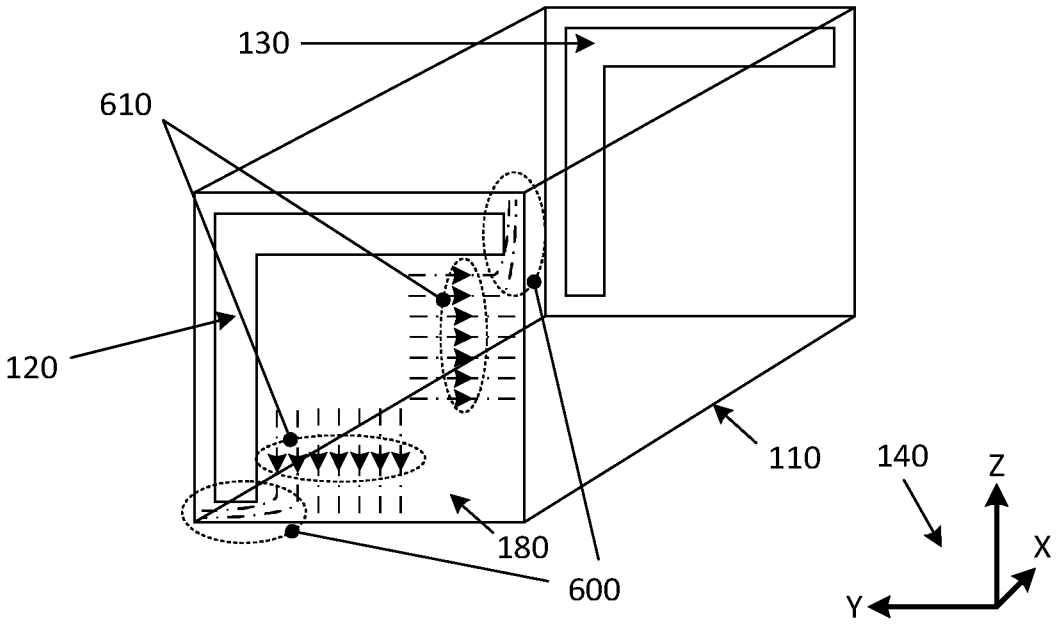



Figure 7

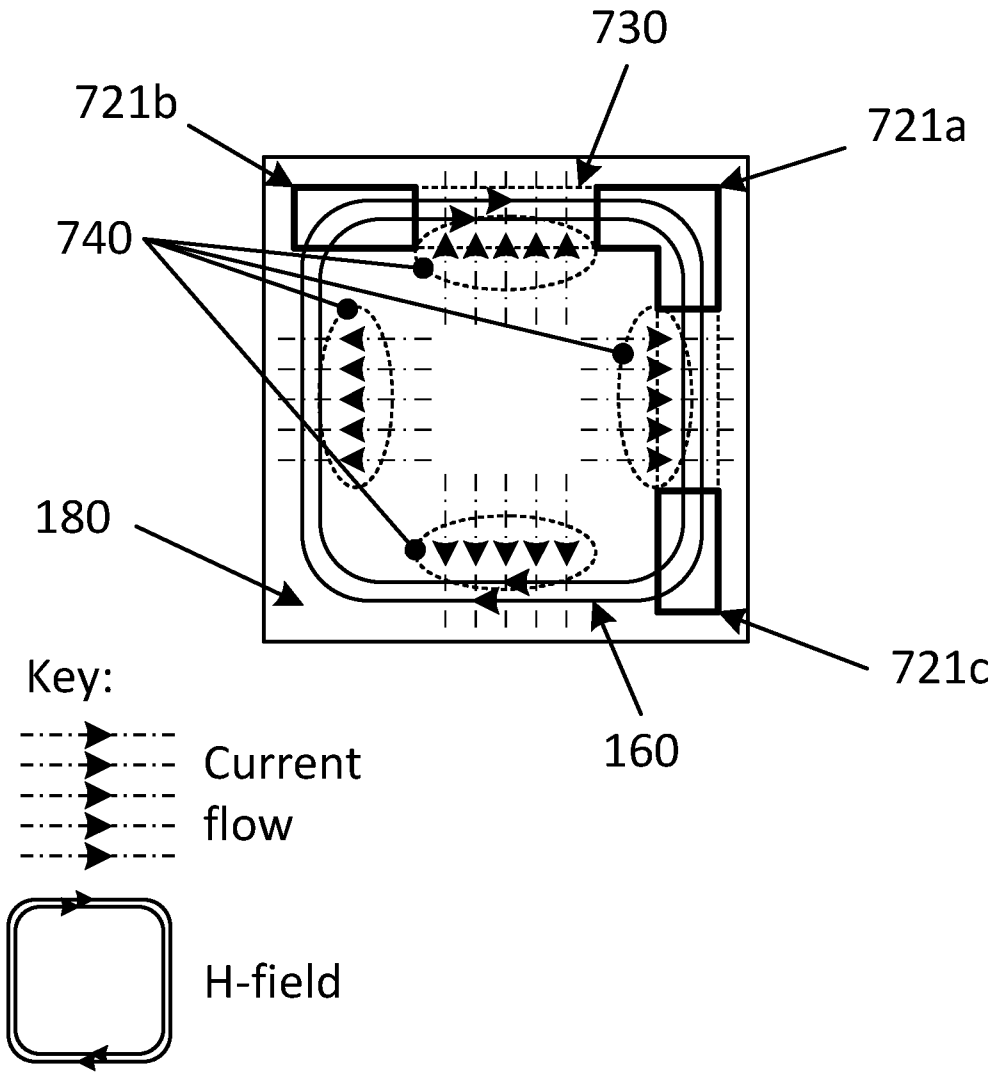



Figure 8

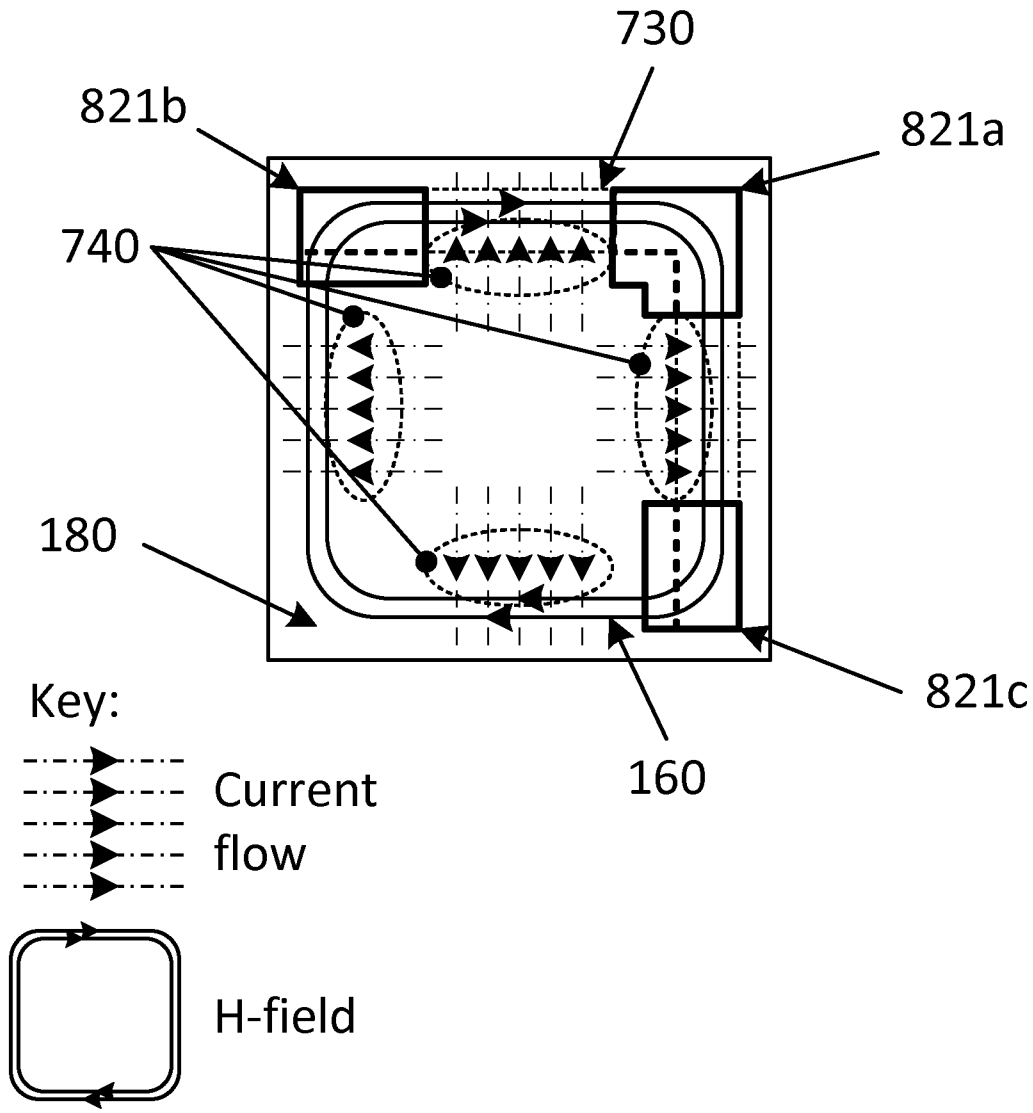



Figure 9

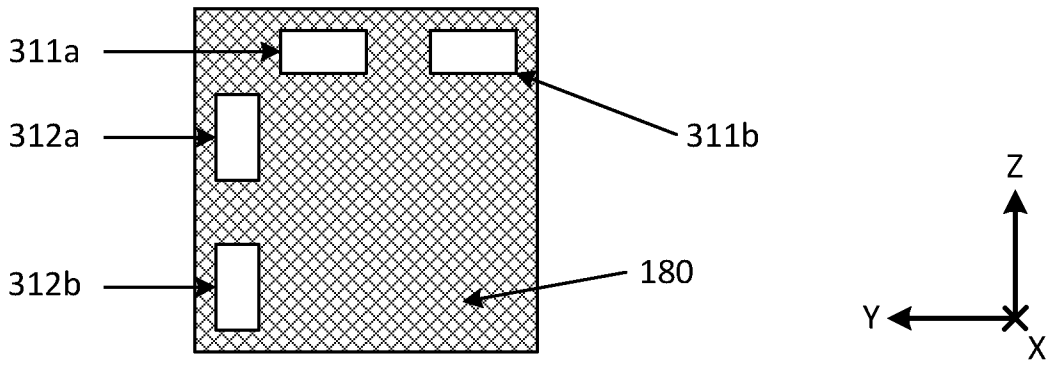



Figure 10 (a)

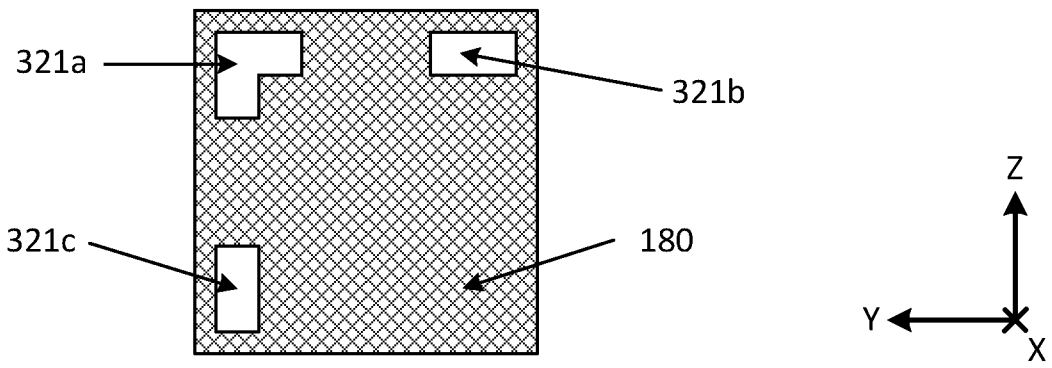



Figure 10 (b)

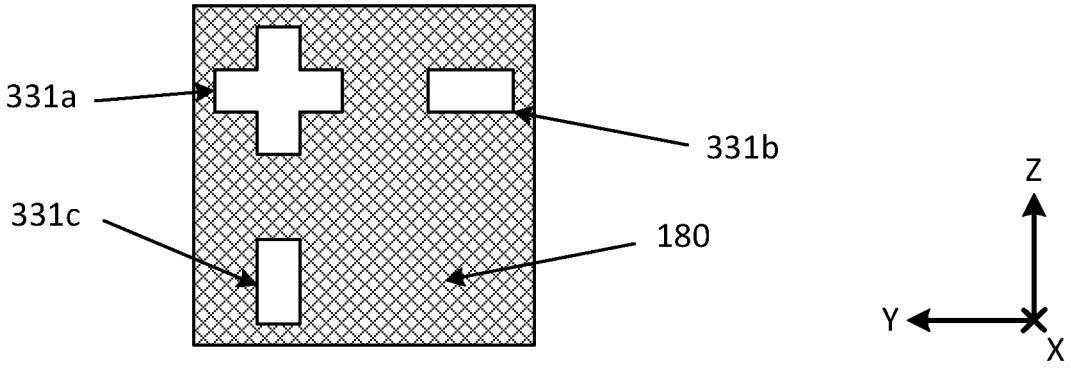



Figure 10 (c)

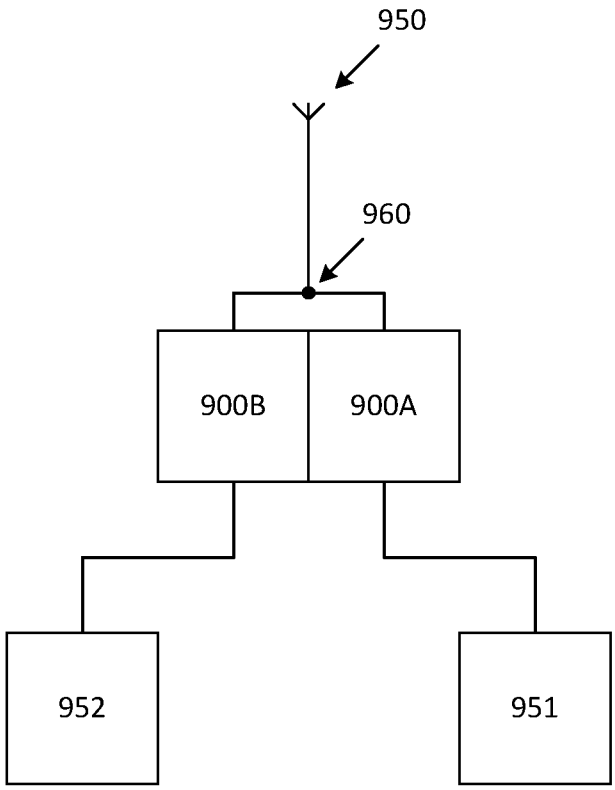



Figure 11 (a)

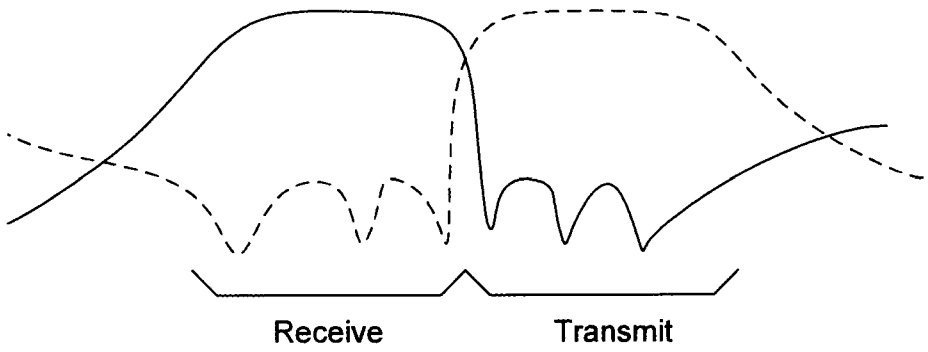



Figure 11 (b)

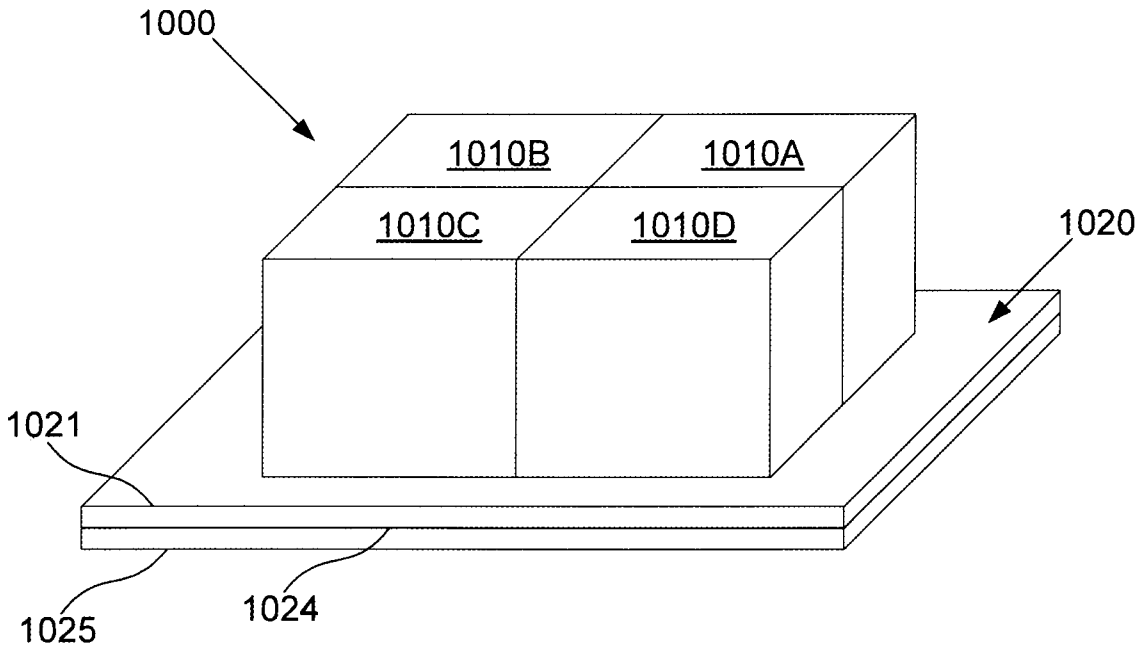



Figure 12

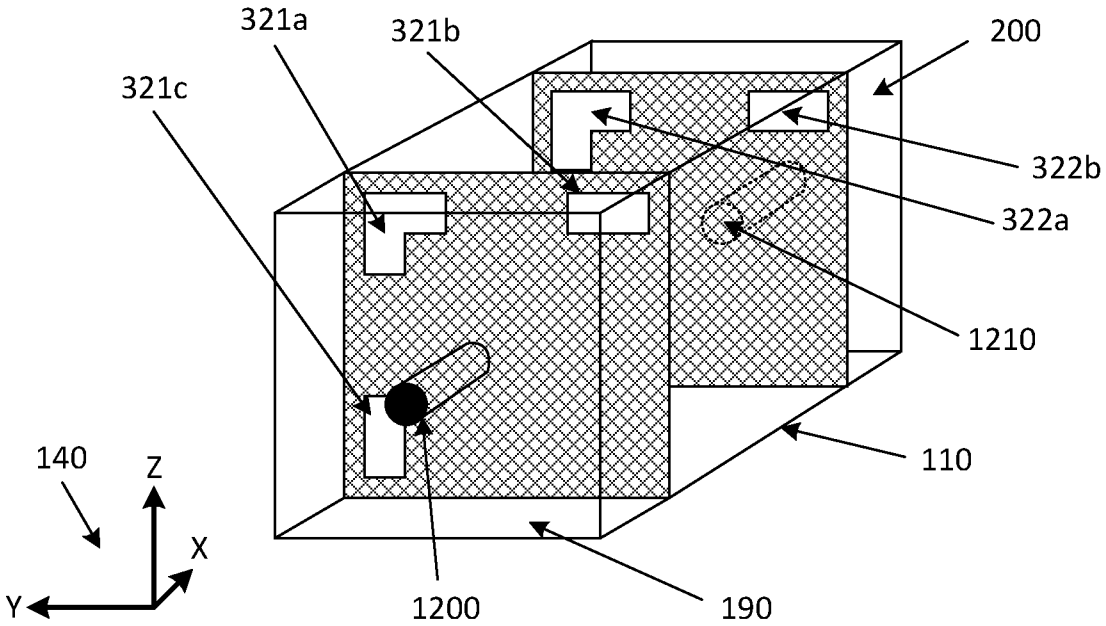



Figure 13 (a)

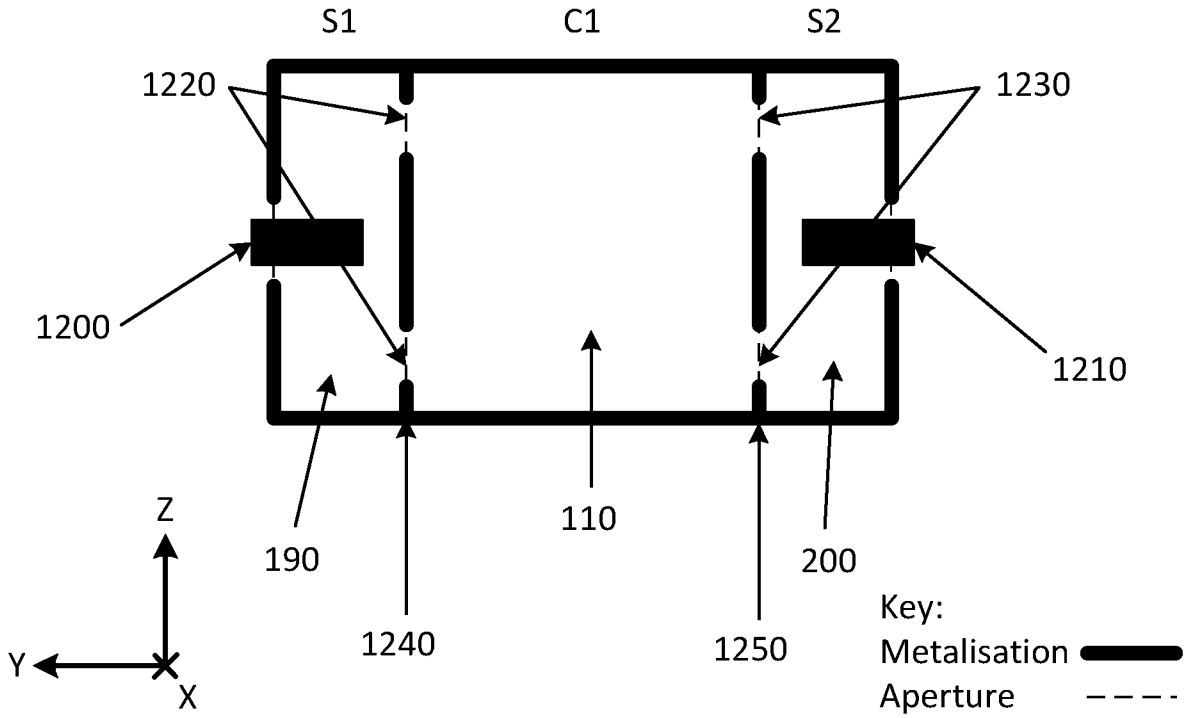

S1
C1
S2
1220
1230
1200
1210
110
190
200
1240
1250
Z
Y
X
Key:
Metalisation
Aperture

Figure 13 (b)

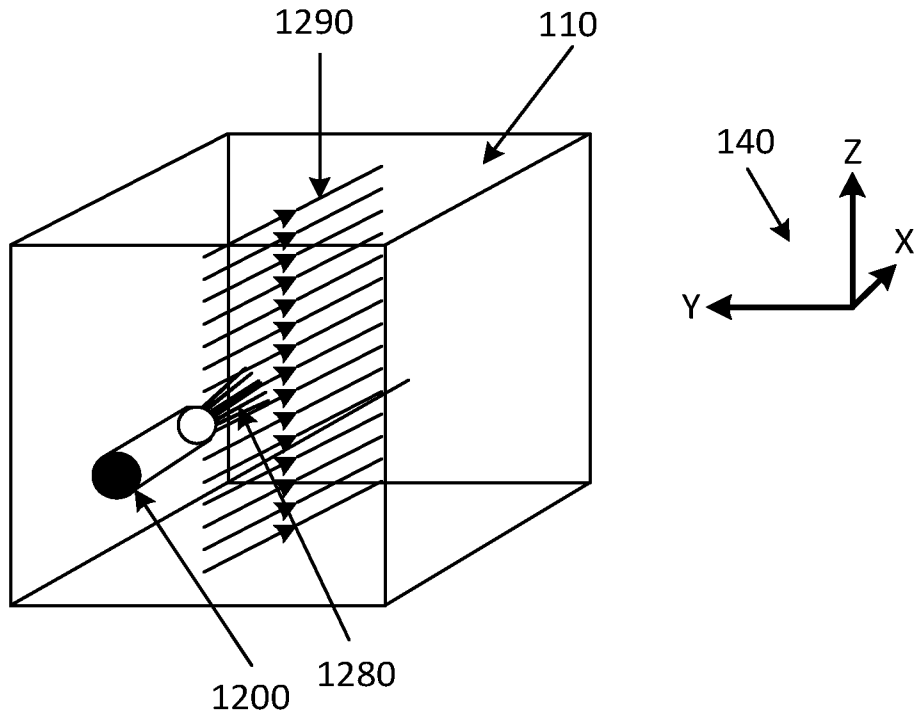



Figure 14 (a)

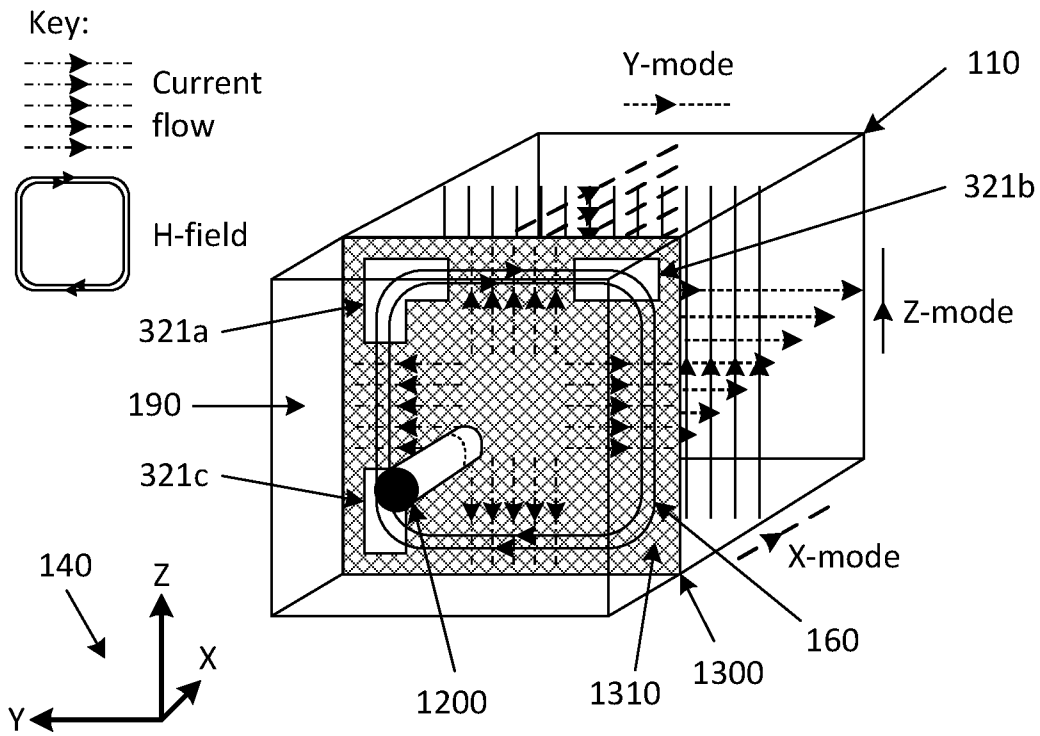



Figure 14 (b)

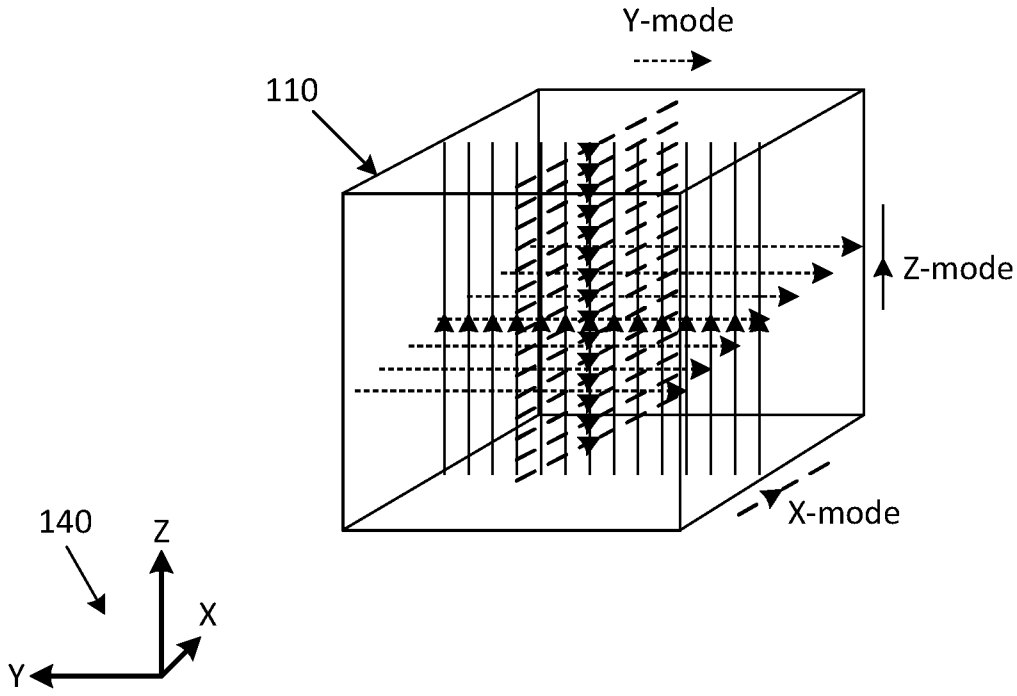



Figure 14 (c)

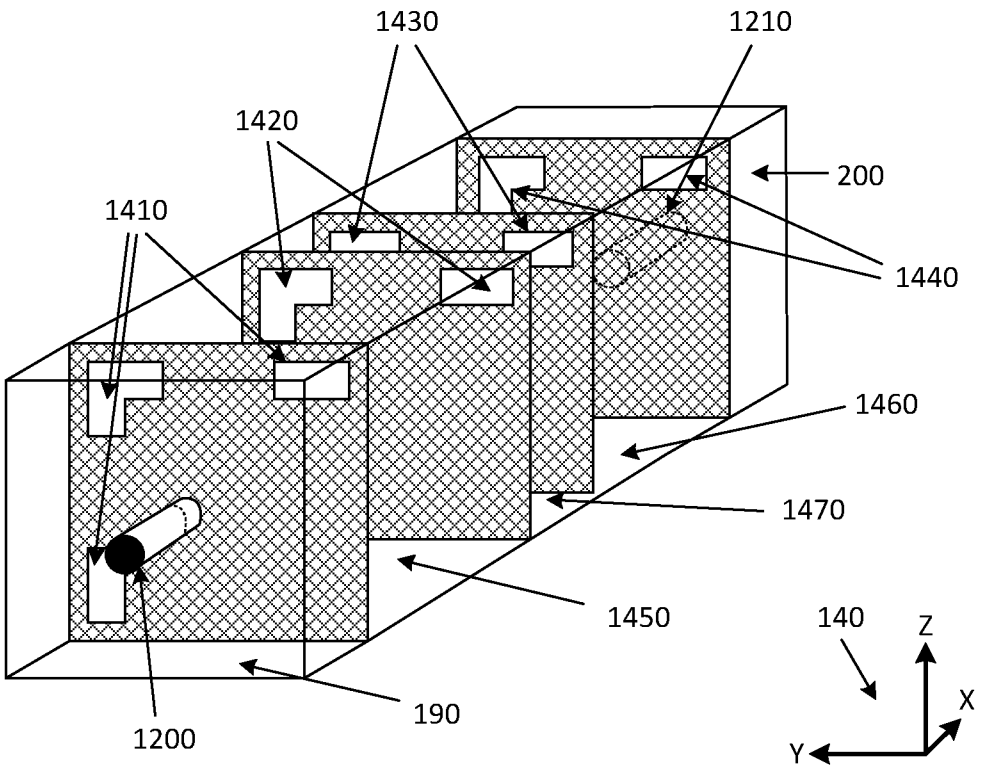



Figure 15

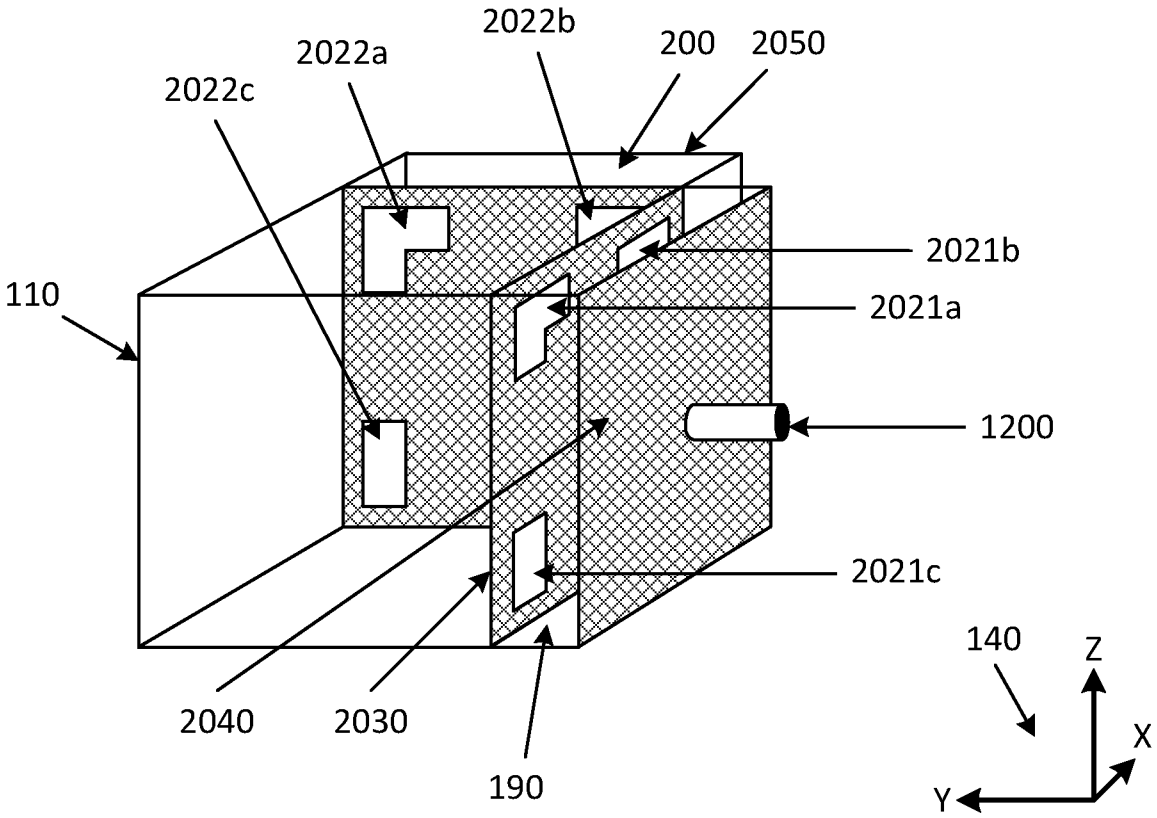

2022b
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Y
2040
2030
190

Figure 16

# INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2014/050517

A. CLASSIFICATION OF SUBJECT MATTER
INV. H01P1/208
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)
H01P

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, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| Y | EP 1 544 939 A1 (RADIO FREQUENCY SYSTEMS INC [US]) 22 June 2005 (2005-06-22)<br>paragraph [0035]<br>paragraph [0040]; figure 1<br>paragraph [0045] - paragraph [0047]<br>paragraph [0064] - paragraph [0068]; figures 17a, 17b<br>paragraph [0072] - paragraph [0076]; figures 21a,21b | 1-18 |
| Y | FR 2 675 952 A1 (ALCATEL TELSPACE [FR])<br>30 October 1992 (1992-10-30)<br>page 1, line 20 - page 2, line 16; figures 1,2<br>page 3, line 23 - page 4, line 16; figures 3-6 | 1-18 |

-/--

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

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"O" document referring to an oral disclosure, use, exhibition or other means

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"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 | Date of mailing of the international search report |
|---|---|
| 20 June 2014 | 27/06/2014 |

| Name and mailing address of the ISA/ | Authorized officer |
|---|---|
| European Patent Office, P.B. 5818 Patentlaan 2<br>NL - 2280 HV Rijswijk<br>Tel. (+31-70) 340-2040,<br>Fax: (+31-70) 340-3016 | Pastor Jiménez, J |

1

Form PCT/ISA/210 (second sheet) (April 2005)

# INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2014/050517

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| Y | ROSENBERG U: "MULTIPLEXING AND DOUBLE BAND FILTERING WITH COMMON-MULTIMODE CAVITIES", IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, IEEE SERVICE CENTER, PISCATAWAY, NJ, US, vol. 38, no. 12, 1 December 1990 (1990-12-01), pages 1862-1871, XP000168520, ISSN: 0018-9480, DOI: 10.1109/22.64567 page 1867, left-hand column, line 10 - right-hand column, line 14; figure 12 page 1868, right-hand column, line 13 - page 1869, left-hand column, line 22; figure 16 | 1-18 |
| A | EP 2 432 070 A1 (COM DEV INT LTD [CA]) 21 March 2012 (2012-03-21) paragraph [0047] - paragraph [0048]; figures 5A, 5B paragraph [0050] - paragraph [0053] paragraph [0067] - paragraph [0070]; figures 9A-9C paragraph [0055] - paragraph [0056]; figures 6A-6D | 1-18 |
| A | CN 102 361 113 A (CN ELECT TECH NO 13 RES INST) 22 February 2012 (2012-02-22) abstract; figures 2-4 | 1-18 |

1

# INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/GB2014/050517

| Patent document cited in search report | Publication date | Patent family member(s) | Publication date |
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| | | US 2005128031 A1 | 16-06-2005 |
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| EP 2432070 A1 | 21-03-2012 | CA 2746908 A1 | 20-03-2012 |
| | | EP 2432070 A1 | 21-03-2012 |
| | | US 2012068792 A1 | 22-03-2012 |
| CN 102361113 A | 22-02-2012 | NONE | |