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(54) Radio-frequency resonator and filter

(57) A radio-frequency resonator comprising a plurality of coaxial line sections (CLS_1 ...CLS_n) connected in cascade, each of said coaxial line sections comprising an inner conductor (C_i) surrounded by an outer conductor (C_{i+1}) of tubular shape, wherein said coaxial line sections are nested within each other, the outer conductor of each said coaxial line section, except an outermost one (C_{n+1}), serving as the inner conductor of another one of said coaxial line sections, the resonator being characterized in that each conductor of each coaxial line section, except the outer conductor of the outermost coaxial line section, has an open-circuit end and an opposite end which is short-circuited to said outer conductor of said outermost coaxial line section, and in that said conductors of said coaxial line sections - except the outer conductor of said outermost coaxial line section - are arranged head-to-tail, their open-circuit and short-circuited ends being alternatively situated on opposite sides of the resonator. Such a resonator achieves a better tradeoff between the conflicting requirements of reduced size and good electrical performances.

A radio-frequency filter comprising a plurality of such radio-frequency resonators mounted adjacent to each other and coupled by openings in the outer conductors of their respective outermost coaxial lines, forming coupling irises.

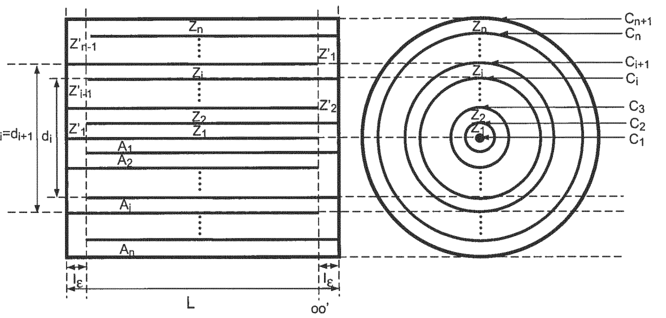


FIG.3

EP 2 882 033 A1

Description

[0001] The invention relates to a radio-frequency resonator, and more specifically to a stepped-impedance coaxial radio-frequency resonator. The invention also relates to a radio-frequency filter comprising a plurality of coupled resonators.

[0002] The expression radio-frequency designates frequency comprised between 3 kHz and 300 GHz. The invention applies more specifically to frequencies belonging to the UHF (Ultra-High-Frequency) band, i.e. comprised between 300 MHz and 3 GHz, although it can also apply to frequencies belonging to the VHF (Very-High-Frequency) band, i.e. comprised between 30 MHz and 300 MHz, and/or to the SHF (Super-High-Frequency) band, i.e. comprised between 3 GHz and 30 GHz, and/or millimetric band, i.e. comprised between 30 GHz and 300 GHz.

[0003] In the fields of electronics and telecommunications there is an ever-increasing need for radio-frequency resonators and filters having a small size, good electric performances (low insertion losses, flat amplitude and linear phase in the pass-band, high rejection outside the pass-band, tunability, etc.) and low cost. Size and mass are particularly critical parameters in comparatively low-frequency applications, i.e. in the VHF and UHF bands. Moreover, size and mass reduction usually comes at the expense of increased insertion losses and decreased quality factor. Figure 1 shows qualitatively the size - insertion losses tradeoff for the main available technologies in the UHF Band.

[0004] Lumped element resonator and filters, which can be used up to the C-band (4 - 8 GHz) are the most compact ones, but are plagued by high insertion losses and have very reduced quality factors (Q= 10 - 50). At the other end of the spectrum, waveguide (or "volume") resonator and filters have very high quality factors (up to 10.000 or more) and low insertion losses, but they are very bulky. Microstrip, coaxial and dielectric resonators offer intermediate performances. Within the coaxial technology, in particular, one can distinguish between uniform air coaxial resonators, with better electrical properties, and uniform dielectric coaxial resonators, more compact but with lower Q and higher insertion losses. Coaxial stepped impedance resonators, constituted by a plurality of coaxial line sections of different characteristic impedance connected in cascade, offer an interesting tradeoff between conflicting electrical and mechanical requirements. The coaxial line sections can be partially or wholly loaded with high-dielectric-constant ceramics for further miniaturization, but again at the expenses of increased losses and reduced Q. Coaxial stepped impedance resonators are described, in particular, by the following papers:

- M. Makimoto and S. Yamashita "Compact Bandpass Filters Using Stepped Impedance Resonator" Proceedings of the IEEE, Vol. 67, No. 1, January 1979;
- S. Yamashita and M. Makimoto "The Q-Factor of Coaxial Resonators Partially Loaded with High Dielectric Constant Microwave Ceramics" , IEEE Transactions on Microwave Theory and Techniques, Vol. MTT-31, No. 6, June 1983; and
- S. Yamashita and M. Makimoto "Miniaturized Coaxial Resonator Partially Loaded with High-Dielectric-Constant Microwave Ceramics", IEEE Transactions on Microwave Theory and Techniques, Vol. MTT-31, No. 9, September 1983;

and by US Patent 4,059,815.

[0005] Document US 4,292,610 describes a stepped-impedance coaxial resonator having a particularly compact structure. As illustrated on figure 2, such a resonator comprises an outer, hollow conductor 1, an inner conductor 2 coaxially mounted within the outer conductor and having a first end short-circuited to a wall of the outer conductor and a second end spaced from the wall of the outer conductor, and an intermediate hollow conductor 3 coaxially mounted between said inner conductor and said outer conductor. Intermediate conductor 3 has a closed end short-circuited to the second end of the inner conductor, and an open end. Conductors 1, 2 and 3 form three coaxial line sections I, II and III having different geometries and therefore, in general, different characteristic impedances Z_1, Z_2 and Z_3. Interestingly, sections II and III are nested with each other. A drawback of this resonator is its lack of design flexibility, as the electrical lengths and the characteristic impedances of the different coaxial line sections are not independent from each other. Moreover, the number of cascaded different coaxial line sections cannot be changed, and the resonator is not easily made tunable.

[0006] The invention aims at curing, at least in part, some or all the above-mentioned drawbacks of the prior art, and more particularly at providing a new resonator structure achieving a better tradeoff between the conflicting requirements of reduced size and good electrical performances.

[0007] An object of the present invention, allowing achieving this aim, is a radio-frequency resonator comprising a plurality of coaxial line sections connected in cascade, each of said coaxial line sections comprising an inner conductor surrounded by an outer conductor of tubular shape, wherein said coaxial line sections are nested within each other, the outer conductor of each said coaxial line section, except an outermost one, serving as the inner conductor of another one of said coaxial line sections, the resonator being characterized in that each conductor of each coaxial line section, except the outer conductor of the outermost coaxial line section, has an open-circuit end and an opposite end which is short-circuited to said outer conductor of said outermost coaxial line section, and in that said conductors of said coaxial line sections - except the outer conductor of said outermost coaxial line section - are arranged head-to-tail, their open-circuit and short-circuited ends being alternatively situated on opposite sides of the resonator.

[0008] According to different embodiments of the invention:

- The radio-frequency resonator may comprise a conductive shell of generally cylindrical shape having a lateral surface, a first base surface and a second base surface, said lateral surface constituting the outer conductor of the outermost coaxial line; a conductor of tubular or rod-like shape, called central conductor, constituting the inner conductor of an innermost coaxial line, said central conductor being contained within said conductive shell and having a first end short-circuited to said first base surface a second end facing said second base surface; and at least one tubular conductor, contained within said conductive shell and containing said central conductor, having an end contacting one said base surface and an opposite end facing the other base surface.
- The radio-frequency resonator may comprise exactly two said coaxial line sections.
- The radio-frequency resonator may comprise exactly three said coaxial line sections.
- An inner conductor of an innermost coaxial line section may be mounted slidably along its longitudinal axis, in such a way that it can be partially extracted from the resonator.
- An inner conductor of a coaxial line section may be electrically connected to a variable capacitor.
- The outer conductor of the outermost coaxial line section may have a rectangular (including square as a particular case) cross-section.
- The radio-frequency resonator may further comprise an excitation rod extending transversally with respect to said coaxial line sections, said excitation rod having a distal end extending to the outside of the resonator and a proximal end contacting or facing a conductor other than said outer conductor of the outermost coaxial line section

[0009] Another object of the invention is a radio-frequency filter comprising a plurality of such radio-frequency resonators mounted adjacent to each other and coupled by openings in the outer conductors of their respective outermost coaxial lines, forming coupling irises. In particular, said radio-frequency resonators may be identical to each other.

[0010] It is important to note that the expression "coaxial line" should be interpreted broadly, as indicating any transmission line section comprising an elongated conductor ("core") surrounded - without direct contact - by a tubular conductor ("shielding"), both conductor having constant cross-sections (i.e. being "cylindrical" in the general sense of the term, not limited to circular-base cylinders) and parallel longitudinal axis. This definition includes e.g. "eccentric coaxial lines", which are not exactly "coaxial" in geometrical terms.

[0011] Additional features and advantages of the present invention will become apparent from the subsequent description, taken in conjunction with the accompanying drawings, wherein:

- Figure 3 is a simplified representation of the structure of a resonator according to an embodiment of the invention, comprising an arbitrary number N of cascaded coaxial sections;
- Figure 4, is an electrical scheme of the resonator of figures 3 ;
- Figure 5 is a simplified representation of the structure of a resonator according to an embodiment of the invention, comprising exactly two cascaded coaxial sections;
- Figures 6A - 6D are plots showing how different parameters characterizing the resonator of figure 5 depend on the characteristic impedance ration of its two cascaded coaxial sections;
- Figure 7 is a simplified representation of the structure of a resonator according to an embodiment of the invention, comprising exactly three cascaded coaxial sections;
- Figure 8 allows comparing the size and the unloaded quality factor Q, of the resonators of figures 5 and 7, of an air uniform coaxial resonator and of a dielectric uniform coaxial resonator ($\varepsilon_r = 90$);
- Figure 9 is the electrical scheme of a second-order Chebyshev band-pass filter according to an embodiment of the invention;
- Figure 10 is an elevation view of a practical implementation of the filter of figure 9;
- Figures 11A and 11B are plots of the measured and simulated values of the scattering parameters S_{11} and S_{12} of the filter of figure 10;
- Figure 12 is the electrical scheme of a sixth-order Chebyshev band-pass filter according to an embodiment of the invention;
- Figures 13A and 13B are plots of the simulated values of the scattering parameters S_{11} and S_{12} of the filter of figure 12;
- Figures 14A and 14B illustrates two tunable resonators according to alternative embodiments of the invention; and
- Figure 15 shows plots of the measured and simulated values of the scattering parameters S_{11} and S_{12} of a second-order tunable filter according to an embodiment of the invention.

[0012] The physical structure of a quarter-wave radio-frequency resonator according to the invention is represented on figure 3. In such a resonator, n>1 coaxial line sections are nested within each other (""matryoshka" structure), disposed head-to-tail - i.e. with open-circuit and short-circuit ends on alternate sides of the resonator. From another point of view, the resonator comprises (n+1) cylindrical conductors C_1 - C_{n+1} whose cross-sections have diameters indicated by d_i, with i=1 to (n+1). The innermost or central conductor C_1 can be either tubular (i.e. hollow) or rod-like (i.e. solid); the outermost conductor C_{n+1} has a lateral surface and two opposite base surfaces, forming a conductive shell. All the conductors, except the outermost one, have an open-circuit end and an opposite end which is short-circuited to the outermost conductor C_{n+1}. Conductors are arranged head-to-toe in the sense that their open-circuit and short-circuited ends are alternatively situated on opposite sides of the resonator (on figure 3, odd-numbered conductors have their left end short-circuited to the left base surface of the outermost conductor, while even-numbered conductors have their right end short-circuited to the right base surface of the outermost conductor). It can be understood that conductors C_1 and C_2 form a first coaxial line section having C_1 as the inner conductor (or "core") and C_2 as the outer conductor (or "shielding"); similarly, C_2 and C_3 form a second coaxial line section having C_2 as its core and C_3 as its shielding, and so on. Every conductor is then simultaneously the core of a coaxial line section and the shielding of another coaxial line section - except the central conductor, which is only a core, and the outermost conductor, which is only a shielding.

[0013] The n coaxial line sections are connected in cascade, and the last coaxial line section (implemented by the C_n and C_{n+1} conductors) is shorted. Therefore, the structure of figure 3 can be represented by the electric scheme of figure 4, wherein each coaxial line section CLS_1 - CLS_n is represented by a quadripole (two-port network) characterized by its characteristic impedance Z_i and its electrical length θ_i with i=1 - n, and Z_{SC} is the impedance of the short-circuit termination. This representation neglects the coupling sections, of physical length l_ε<<L (L being the physical length of the resonator) and characteristic impedance Z'_i. It should be noted that the discontinuities at the end of each tubular conductor are very favorable to the coupling of TEM modes propagating along the coaxial line sections.

[0014] In the present example it is assumed that all the coaxial line sections are concentric and have circular cross-section but, as discussed above, this is not essential.

[0015] TEM modes can be excited inside the resonator by different means known in the art. For example a rod (not represented here, but see CR_1, CR_2 on figure 10) can extend transversally to the axis of the coaxial line sections, having a "distal" end connected to the outside of the resonator through an opening in the lateral surface of the outermost conductor, and a "proximal" end contacting - or being spaced from - another conductor. The distal end can be connected to the core of a RF feeding coaxial cable, the shielding of which is connected to the outermost conductor. Alternatively, TEM modes can be also excited e.g. by an iris, or by a "current loop" obtained by forming a loop with the core of the RF feeding coaxial cable, whose distal end contacts the outermost conductor.

[0016] Let L be the physical length of all the coaxial line sections, ε_{ri} its relative dielectric constant of the i-th section, d_i and D_i the diameters of the conductors forming its core and shielding, respectively (it will be noted that the i-th conductor, with i>1, has an inner diameter equal to D_{i-1} and an outer diameter equal to d_i; if the thickness of the conductor is negligible, $D_{i-1} \cong d_i$; this approximation was used when discussing figure 3). Then, at frequency f, the electrical length θ_I is given by:

$$\theta_i = \beta_i L \qquad (1)$$

where

$$\beta_i = \frac{2\pi\sqrt{\varepsilon_{ri}}}{\lambda_0} \qquad (2)$$

is the propagation constant (λ_0=c/f being the wavelength in vacuum, c being the light speed in vacuum), and - assuming losses negligible - the characteristic impedance Z_i is given by:

$$Z_i = \frac{1}{2\pi} . \sqrt{\frac{\mu_0}{\varepsilon_{ri} . \varepsilon_0}} \ln \frac{D_i}{d_i} \qquad (3)$$

ε_0 and μ_0 being the electrical permittivity and the magnetic permeability of vacuum.

[0017] As it is well known in the art of electric networks, each two-port network can be represented by an ABCD matrix, or chain matrix; the overall chain matrix of the resonator, [ABCD] is obtained by orderly multiplying the individual chain matrices of the different coaxial line sections, and $\begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix}$ matrices representing the crossed connections between them:

$$[ABCD] = \begin{bmatrix} \cos\theta_1 & jZ_1 \sin\theta_1 \\ j\frac{\sin\theta_1}{Z_1} & \cos\theta_1 \end{bmatrix} . \begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix} . \begin{bmatrix} \cos\theta_2 & jZ_2 \sin\theta_2 \\ j\frac{\sin\theta_2}{Z_2} & \cos\theta_2 \end{bmatrix}$$

$$\cdots\cdots\cdots \begin{bmatrix} \cos\theta_i & jZ_i \sin\theta_i \\ j\frac{\sin\theta_i}{Z_i} & \cos\theta_i \end{bmatrix} . \begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix} \cdots\cdots\cdots$$

$$. \begin{bmatrix} \cos\theta_{n-1} & jZ_{n-1} \sin\theta_{n-1} \\ j\frac{\sin\theta_{n-1}}{Z_{n-1}} & \cos\theta_{n-1} \end{bmatrix} . \begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix} . \begin{bmatrix} \cos\theta_n & jZ_n \sin\theta_n \\ j\frac{\sin\theta_n}{Z_n} & \cos\theta_n \end{bmatrix} \qquad (4)$$

[0018] The A, B, C and D elements of [ABCD] allow determining the impedance as seen in the OO' plane of the open circuit end of the central conductor C_1:

$$Zr_1 = \frac{V_1}{I_1} = \frac{Z_{sc}A + B}{Z_{sc}C + D} = \frac{B}{D} \qquad (5)$$

This, in turn, allows determining the frequency at which the resonance condition $Zr_i = \infty$ is satisfied.

[0019] Generalization of equations (1) to (5) to the case of coaxial sections having different length l_i is straightforward.

[0020] A detailed analysis of the electrical properties of the general structure of figure 3 is cumbersome; therefore, such an analysis will only be carried out for the case of a two-section (i.e. three-conductor) resonator, illustrated on figure 5. This turns out to be the preferred embodiment of the invention. It should be noted that, in the structure of figure 5, the conductive shell formed by the outermost conductor C_3 need not be completely closed; in particular one or both of its base surfaces might comprise openings.

[0021] It follows from equations 1 to 5 that, for n=2:

$$Zr_1 = Z_1 \frac{jZ_2 \tan\theta_2 + jZ_1 \tan\theta_1}{Z_1 - Z_2 \tan\theta_2 \tan\theta_1} \qquad (6)$$

[0022] The resonance condition $Zr_1=\infty$ is satisfied when:

$$Z_1 - Z_2 \tan\theta_2 \tan\theta_1 = 0 \quad (7)$$

[0023] By defining M as the characteristic impedance ratio $M=Z_2/Z_1$, equation (7) becomes:

$$\frac{1}{M} = \tan\theta_1 \tan\theta_2 \quad (8)$$

[0024] If $\theta_1=\theta_2=\theta_0$ (same-length sections, filled with a same dielectric e.g. air), then:

$$\tan\theta_0 = \sqrt{\frac{1}{M}} \quad (9)$$

and the resonance frequency (more precisely: the fundamental resonance frequency) F_0 is given by:

$$F_0 = \frac{c}{2\pi L\sqrt{\varepsilon_r}} \tan^{-1}\sqrt{\frac{1}{M}} \quad (10)$$

[0025] Figure 6A illustrates, the relationship between θ_0 and M expressed by equation (9).

[0026] The first spurious resonance is given by:

$$F_{S1} = \left(\frac{\pi}{tan^{-1}\sqrt{\frac{1}{M}}} - 1\right) F_0 \quad (11)$$

[0027] Figures 6B illustrates the relation between the ratio F_{S1}/F_0 and characteristic impedance contrast M.

[0028] Figures 6C and 6D have been obtained by considering the case of a particular implementation wherein:

- central conductor C_1 is a cylindrical rod with d_1=7mm, made of brass;
- conductor C_2 is a 1-mm thick aluminum cylinder whose internal diameter D_2 is varied between 7.2 to about 34 mm;
- conductor C_3 is also made of aluminum; it has a square cross section, with a 34 mm side (rectangular geometry - of which a square cross-section is a particular case - is useful for implementing filters, as it will be discussed later);
- the resonator is air-filled;
- the length of the coaxial sections formed by C_2 and C_3 is 30.6 mm and that of the coupling sections is 2mm; and
- the length of the coaxial sections formed by C_1 and C_2 is 28.6 mm.

[0029] On figure 6C, two curves illustrate, the relationship between the ratio F_{S1}/F_0 and M. One of said curves correspond to theoretical results, the other one to numerical electromagnetic simulations. The difference between theoretical and simulation results is small, and can be traced back to the coupling sections neglected by the analytical theory. A third curve illustrates, the relationship between the ratio L/L_0 and M, where L_0 is the length of the inventive resonator and L that of an equivalent uniform quarter-wave air coaxial resonator. When M increases, the resonant frequency decreases, and L increases while L_0 remains constant; as a consequence (L/L_0) increases, as shown by the figure.

[0030] Figures 6D illustrates the unloaded quality factor Q as a function of M.

[0031] Inspection of figures 6A - 6D shows that:

- To minimize the electrical (and therefore physical) length, and to maximize the F_{S1}/F_0 ratio, it is necessary to choose a high characteristic impedance contrast M (Z_2>>Z_1), which can be achieved by reducing D_1 (and therefore d_2) while maintaining d_1 and D_3 constant; the intermediate conductor C_2 is then only slightly larger than the central conductor C_1 and much smaller than C_3.
- To minimize the F_{S1}/F_0 ratio, it is necessary to choose a low characteristic impedance contrast M (Z_1>>Z_2), which can be achieved by increasing D_1 (and therefore d_2) while maintaining d_1 and D_2 constant; the intermediate conductor C_2 is then much larger than the central conductor C_1 and slightly smaller than C_3
- Q is maximal for M=1 (Z_2=Z_1).

[0032] In the case M≅49 (corresponding to Z_1=1.7Ω, Z_2=82.9Ω, D_1-d_1=100 μm), F_0=220 MHz and F_{S1}=4.7 GHz, i.e. F_{S1}/F0≅21. A uniform quarter-wave, air-filled coaxial resonator having the same resonant frequency F_0 would have a length of 341 mm. The invention allows then a length reduction of a factor 11.14.

[0033] In the case M≅0.1 (corresponding to Z_1=87.3Ω, Z_2=8.2Ω), F_0=2 GHz and F_{S1}=2.9 GHz, i.e. F_{S1}/F_0=1.45. The length reduction with respect to an uniform quarter-wave coaxial resonator is small; however, the availability of two close resonant frequencies can be useful to implement dual-band filters.

[0034] Figure 7 is similar to figure 5, except in that it illustrates a three-section (and then four-conductor) resonator, whose properties depend on two characteristic impedance contrast factors, M1=Z_3/Z_2 and M2=Z_2/Z_1.

[0035] Figure 8 allows comparing at 435 MHz the lengths and unloaded quality factors of: a two-section air-filled resonator according to an embodiment of the invention (cf. figure 5), a three-section air-filled resonator according to another embodiment of the invention (cf. figure 7), an uniform quarter-wave air-filled coaxial resonator with characteristic impedance Z_c=77Ω corresponding to the optimal unloaded quality factor Q=3 100, and an uniform quarter-wave dielectric coaxial resonator with ceramic relative permittivity Er=90 and loss tangent tg(δ)=10^{-3}. All the resonators have a square cross section with a side length of 34mm. Both the two- and the three-section resonators have a substantially higher quality factor than the uniform dielectric resonator, and only a slightly greater length. From a different point of view, they are much shorter than the uniform air-filled resonator, at the expense of a moderate reduction of the quality factor.

[0036] The application of the inventive filters to the realization of band-pass filters will now be discussed. Extrapolation to the case of pass-band band-stop filters is straightforward.

[0037] Figure 9 shows the electrical scheme of a second-order band-pass filter comprising a parallel connection of two identical 2-section resonators R1 and R2 between admittance inverters. K_{01} and K_{23} are the external coupling and K_{12} the coupling between the resonators. The values of these parameters are determined by a conventional Chebyshev synthesis.

[0038] Figure 10 illustrates a possible and non limitative, physical implementation of the filter of figure 9. The outermost conductors C_3^1, C_3^2 of both resonators are constituted by a common aluminum casing AC, partitioned by an internal wall SW which does not extend on the whole length of the resonators so as to form, with the back wall of the casing, a coupling iris CI. Two tuning screws TS_1, TS_2 are provided to adjust the coupling strength, and therefore the coupling K_{12}. The intermediate conductors C_2^1, C_2^2 of both resonators are constituted by respective aluminum tubes fixed to the face wall of the aluminum casing (not shown, to make the inner structure of the filter visible) and not contacting the back wall; their central conductors C_1^1, C_1^2 are constituted by brass rods fixed to the back wall of the casing and not contacting the face wall. Two excitations rods ER_1 and ER_2 extend transversally; their proximal ends contact the intermediate conductors C_2^1, C_2^2 while their distal ends exit the resonator through respective openings in the aluminum casing. The distal ends of the excitation rods are connected - trough conventional connectors - to the cores of two coaxial cables, whose shielding are connected to the aluminum casing and to the ground thorough respective conducting chocks (visible on the sides of the casing). The dimensions of the different elements are:

- diameters of the central conductors: d_1^1=d_1^2= 7mm;
- spacing between the central and the intermediate conductors: 500 μm;
- lengths of the intermediate conductors C_2^1, C_2^2: 30.6 mm and that of the coupling sections is 8 mm;
- thickness of the intermediate conductors C_2^1, C_2^2: 1 mm;
- lengths of the central conductors C_1^1 C_1^2: 32.8mm;
- inner dimensions of the aluminum casing: 34 mm ;
- outer dimensions of the aluminum casing with back and frontal walls: 86 mm x 50 mm x 43 mm.

[0039] A smaller size (e.g. a reduction of the longitudinal dimension from 43 to 25 mm) could be achieved using more sophisticated manufacturing techniques, such as electroforming.

[0040] The requirements of the 2nd order filters are the following: central frequency F_0=435 MHz, relative pass bandwidth of 4.6% and 0.01 dB ripple within the pass band.

[0041] Figures 11A and 11 B show the frequency dependence of the scattering parameters S_{11} and S_{12}, obtained from simulation and from measurement. Figure 11A is a narrow-band representation, while figure 11B is a large-band one, showing the first spurious frequency F_{S1}, with F_{S1}=3.8GHz i.e. $(F_{S1}/F_0)\cong 9$.

[0042] The requirements of the 6th order filter are the following: central frequency F_0=435 MHz, relative pass bandwidth of 6.8%, matching level better than 20 dB within the pass band.

[0043] Figure 12 shows the electrical scheme of a 6th order filter comprising six identical two-section resonators, with coupling constants K_{12}, K_{23}, K_{34}, K_{45}, K_{56} and K_{67}. The K_{16} coupling is important as it allows introducing two transmission zeros near the pass band.

[0044] Physically, the resonators can be arranged in a 3x2 matrix. Figures 13A and 13B are, respectively, narrow-band and large-band representations of the frequency dependence of scattering parameters S_{11} and S_{12}. Figure 13A also shows (thick line and dotted line) the required filter specification.

[0045] Resonators according to the invention, and therefore filters built from them, can be made tunable in several ways, two of which are illustrated on figures 14A and 14B.

[0046] In the embodiment of figure 14A, an electrical motor EM is used to move the central conductor C_1 in an axial direction, thus changing the length of the portion of it which is contained within the resonator. This changes the physical - and electrical - length of the first coaxial line section, and therefore the resonance frequency. This allows broad, but slow, tunability. Figure 14B shows an alternative embodiment, wherein a variable capacitor (implemented e.g. by a varactor diode) is connected between the central conductor C_1 (or an intermediate conductor, such as C_2) and the ground. This allow faster tuning, but in a narrower range, and reduces the quality factor. It is clear that different tuning mechanisms (e.g. those of figures 14A and 14B) can be combined in a same device.

[0047] Figure 15 shows the frequency dependence of the scattering parameters S_{11} and S_{12} of a tunable filter, for 5 different values P1 - P5 of the central frequency, spanning the 435 MHz - 1.63 GHz range.

Claims

1. A radio-frequency resonator comprising a plurality of coaxial line sections (CLS_1 ...CLS_n) connected in cascade, each of said coaxial line sections comprising an inner conductor (C_i) surrounded by an outer conductor (C_{i+1}) of tubular shape, wherein said coaxial line sections are nested within each other, the outer conductor of each said coaxial line section, except an outermost one (C_{n+1}), serving as the inner conductor of another one of said coaxial line sections, the resonator being **characterized in that** each conductor of each coaxial line section, except the outer conductor of the outermost coaxial line section, has an open-circuit end and an opposite end which is short-circuited to said outer conductor of said outermost coaxial line section, and **in that** said conductors of said coaxial line sections - except the outer conductor of said outermost coaxial line section - are arranged head-to-tail, their open-circuit and short-circuited ends being alternatively situated on opposite sides of the resonator.

2. A radio-frequency resonator according to claim 1, comprising:

   - a conductive shell (C_{n+1}) of generally cylindrical shape having a lateral surface, a first base surface and a second base surface, said lateral surface constituting the outer conductor of the outermost coaxial line;
   - a conductor of tubular or rod-like shape, called central conductor (C_1), constituting the inner conductor of an innermost coaxial line, said central conductor being contained within said conductive shell and having a first end short-circuited to said first base surface a second end facing said second base surface; and
   - at least one tubular conductor (C_2), contained within said conductive shell and containing said central conductor, having an end contacting one said base surface and an opposite end facing the other base surface.

3. A radio-frequency resonator according to any of the preceding claims, comprising exactly two said coaxial line sections.

4. A radio-frequency resonator according to any of claims 1 or 2, comprising exactly three said coaxial line sections.

5. A radio-frequency resonator according to any of the preceding claims, wherein an inner conductor (C_1) of an innermost coaxial line section is mounted slidably along its longitudinal axis, in such a way that it can be partially extracted from the resonator.

6. A radio-frequency resonator according to any of the preceding claims, wherein an inner conductor (C_i) of a coaxial line section is electrically connected to a variable capacitor (VC).

7. A radio-frequency resonator according to any of the preceding claims, wherein the outer conductor of the outermost coaxial line section has a rectangular cross-section.

8. A radio-frequency resonator according to any of the preceding claims, further comprising an excitation rod (ER_1, ER_2) extending transversally with respect to said coaxial line sections, said excitation rod having a distal end extending to the outside of the resonator and a proximal end contacting or facing a conductor other than said outer conductor of the outermost coaxial line section

9. A radio-frequency filter comprising a plurality of radio-frequency resonators (R1, R2) according to any of the preceding claims mounted adjacent to each other and coupled by openings (CI) in the outer conductors of their respective outermost coaxial lines, forming coupling irises.

10. A radio-frequency filter according to claim 9, wherein said radio-frequency resonators (R1, R2) are identical to each other.

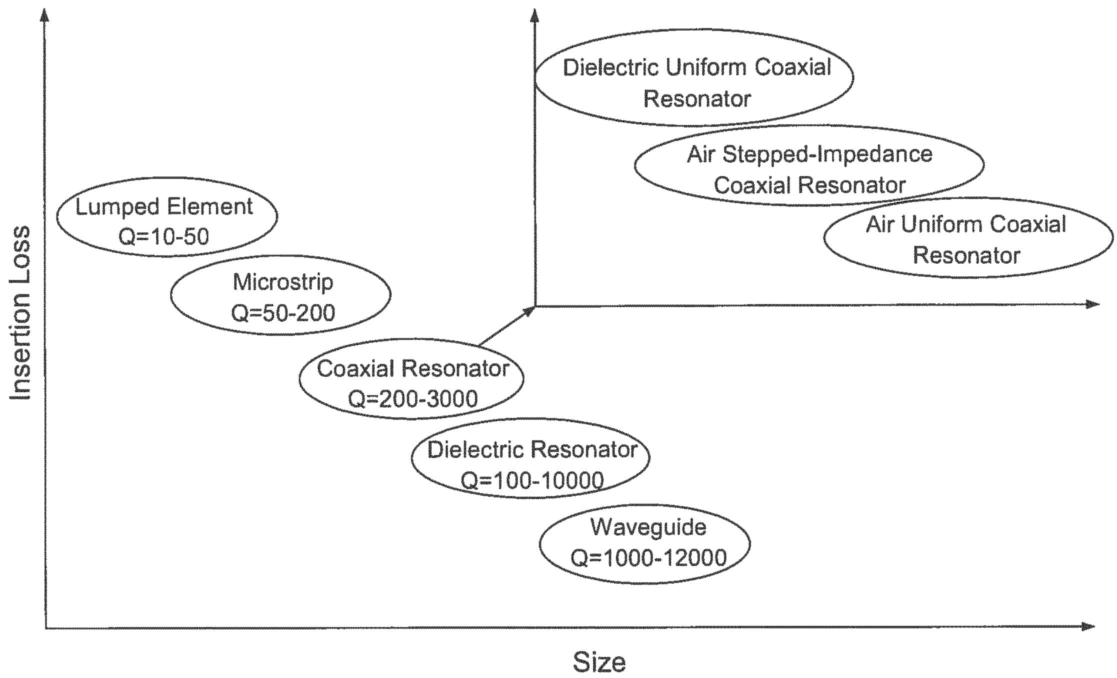

Insertion Loss
Size
Lumped Element
Q=10-50
Microstrip
Q=50-200
Coaxial Resonator
Q=200-3000
Dielectric Resonator
Q=100-10000
Waveguide
Q=1000-12000
Dielectric Uniform Coaxial
Resonator
Air Stepped-Impedance
Coaxial Resonator
Air Uniform Coaxial
Resonator

FIG.1

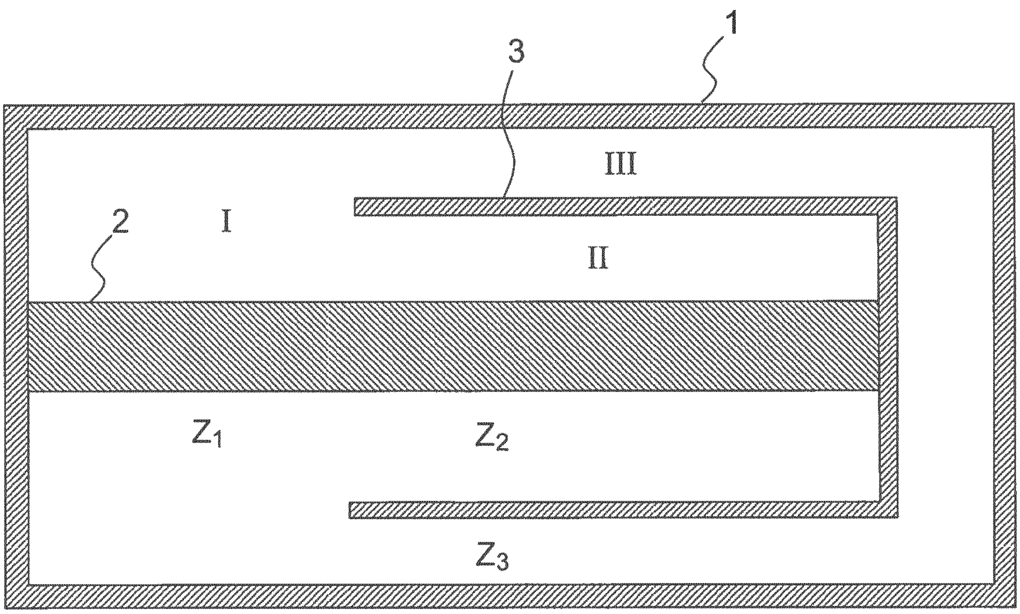

1
3
2
I
II
III
Z1
Z2
Z3

FIG.2

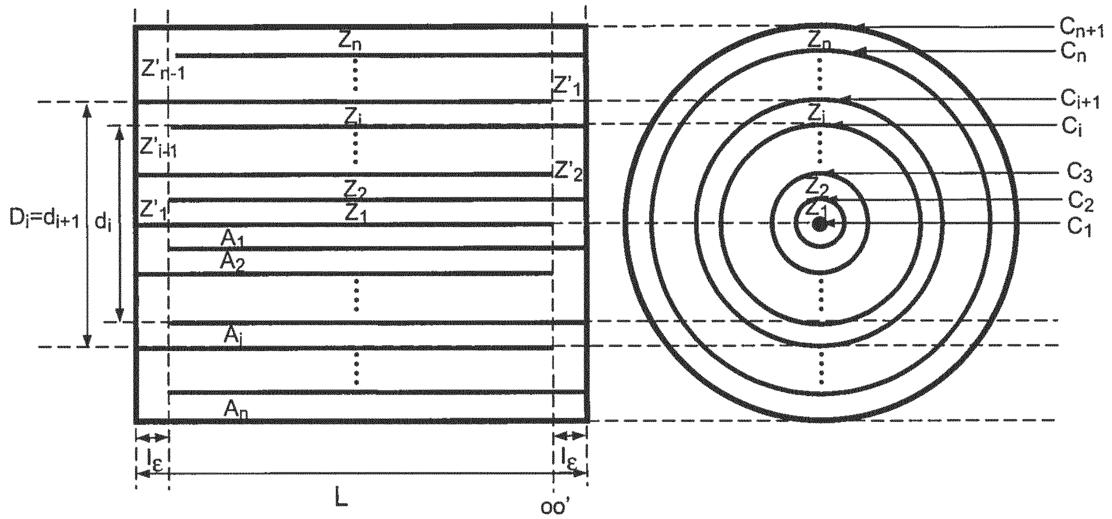


FIG.3

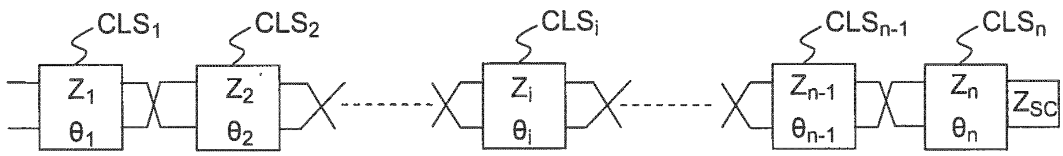


FIG.4

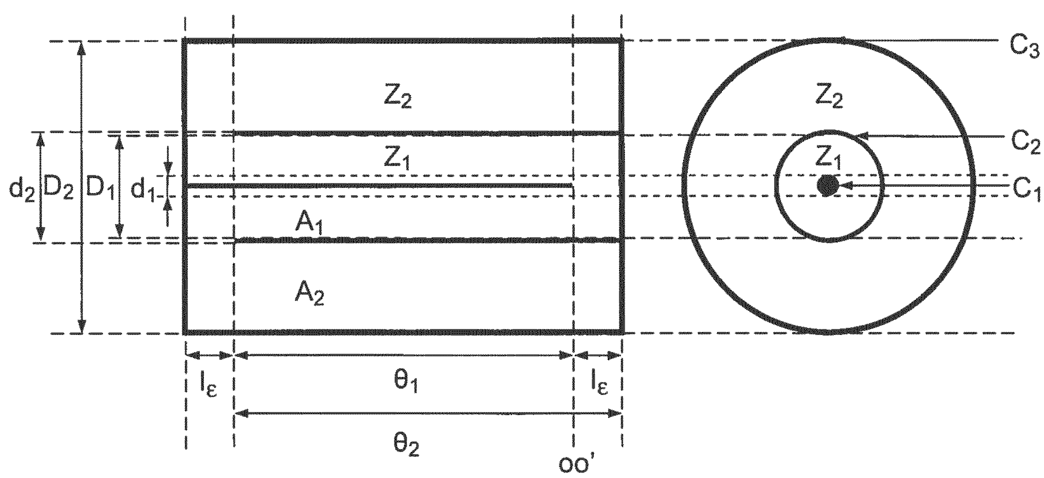
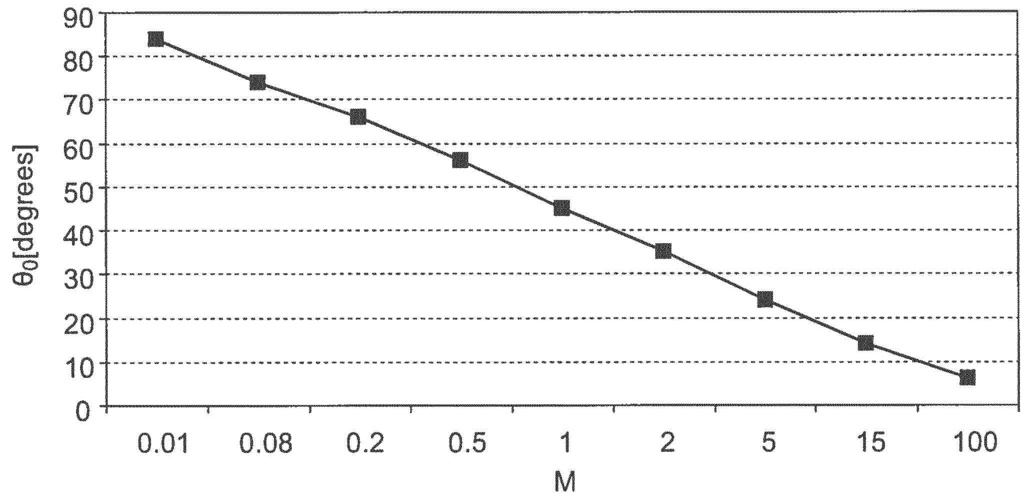
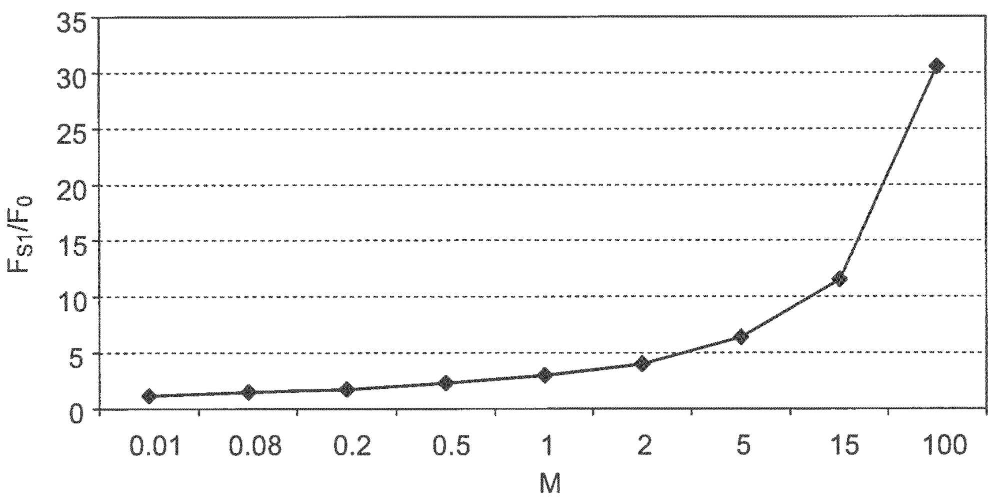


FIG.5



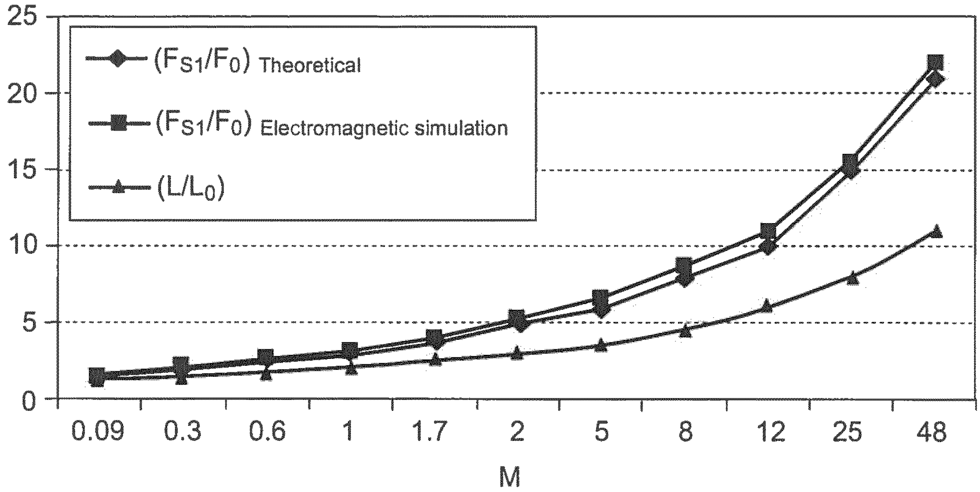
90
80
70
60
50
40
30
20
10
0
θ0[degrees]
0.01
0.08
0.2
0.5
1
2
5
15
100
M

FIG.6A



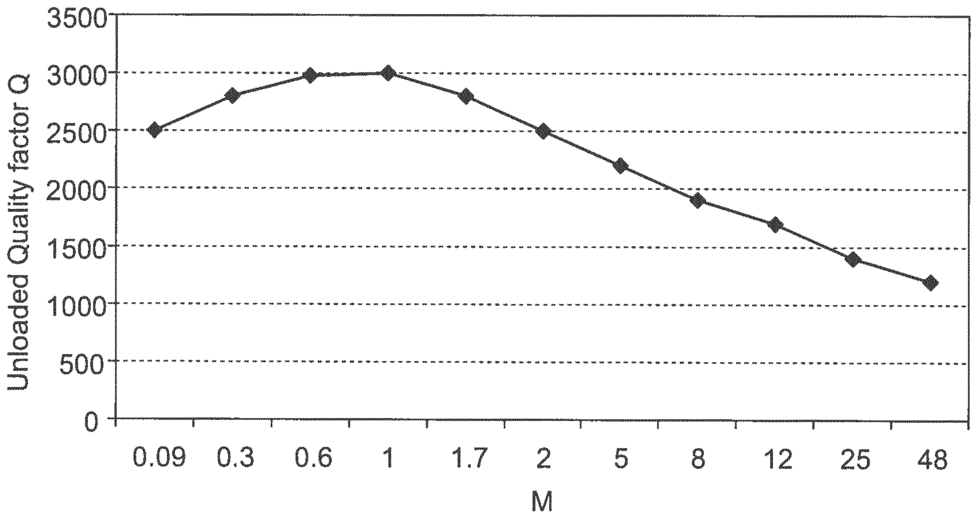
35
30
25
20
15
10
5
0
FS1/F0
0.01
0.08
0.2
0.5
1
2
5
15
100
M

FIG.6B



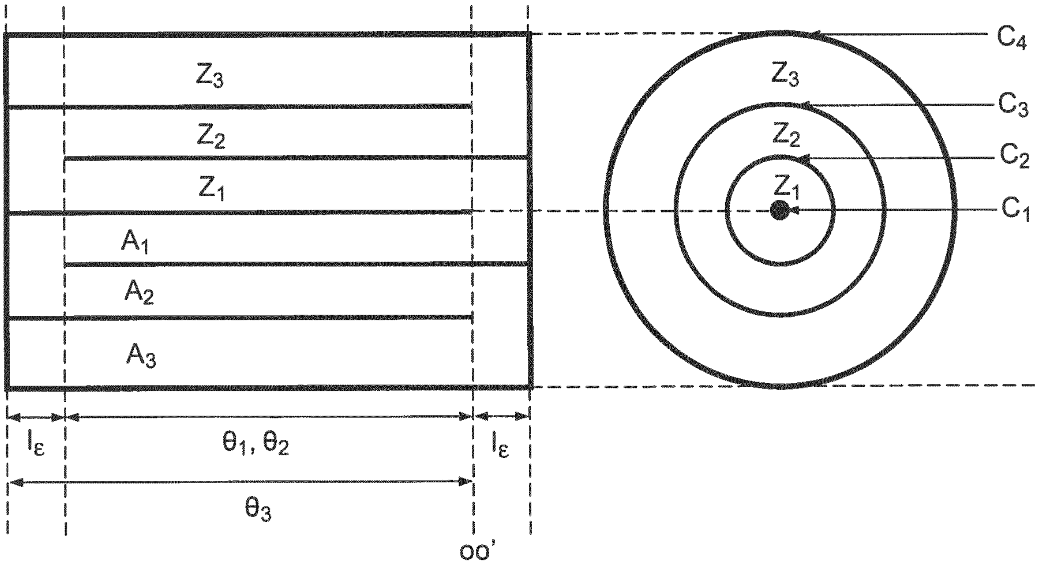
25
20
15
10
5
0
(F_{S1}/F_0) Theoretical
(F_{S1}/F_0) Electromagnetic simulation
(L/L_0)
0.09
0.3
0.6
1
1.7
2
5
8
12
25
48
M

FIG.6C



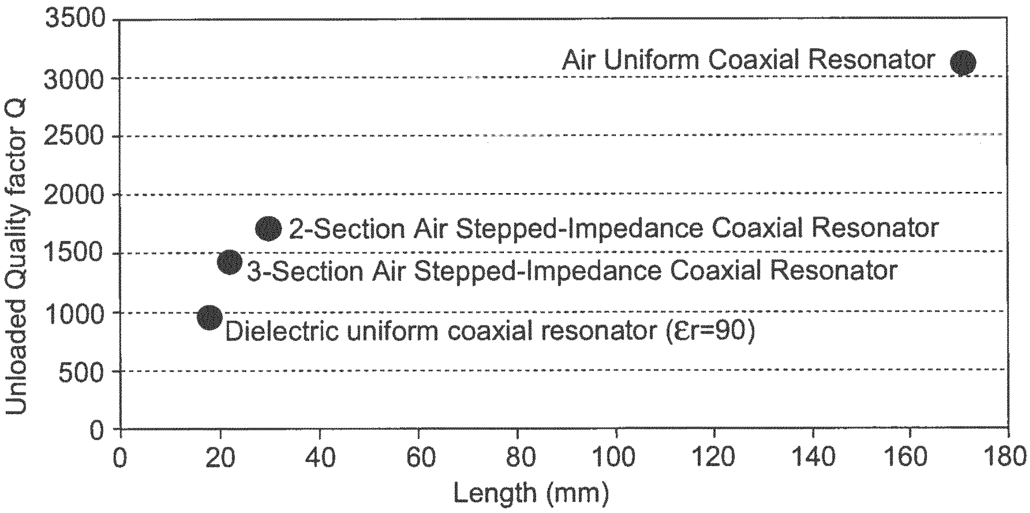
Unloaded Quality factor Q
3500
3000
2500
2000
1500
1000
500
0
0.09
0.3
0.6
1
1.7
2
5
8
12
25
48
M

FIG.6D



Z3
Z2
Z1
A1
A2
A3
lε
θ1, θ2
lε
θ3
oo'
C4
C3
C2
C1

FIG.7



Air Uniform Coaxial Resonator
2-Section Air Stepped-Impedance Coaxial Resonator
3-Section Air Stepped-Impedance Coaxial Resonator
Dielectric uniform coaxial resonator (εr=90)
Unloaded Quality factor Q
Length (mm)

FIG.8

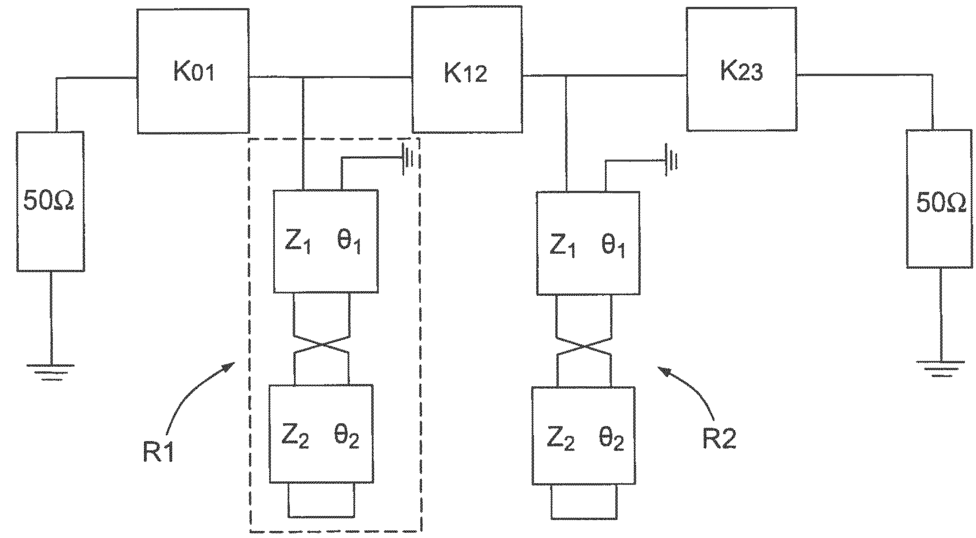

K01
K12
K23
50Ω
50Ω
Z1 θ1
Z2 θ2
Z1 θ1
Z2 θ2
R1
R2

FIG.9

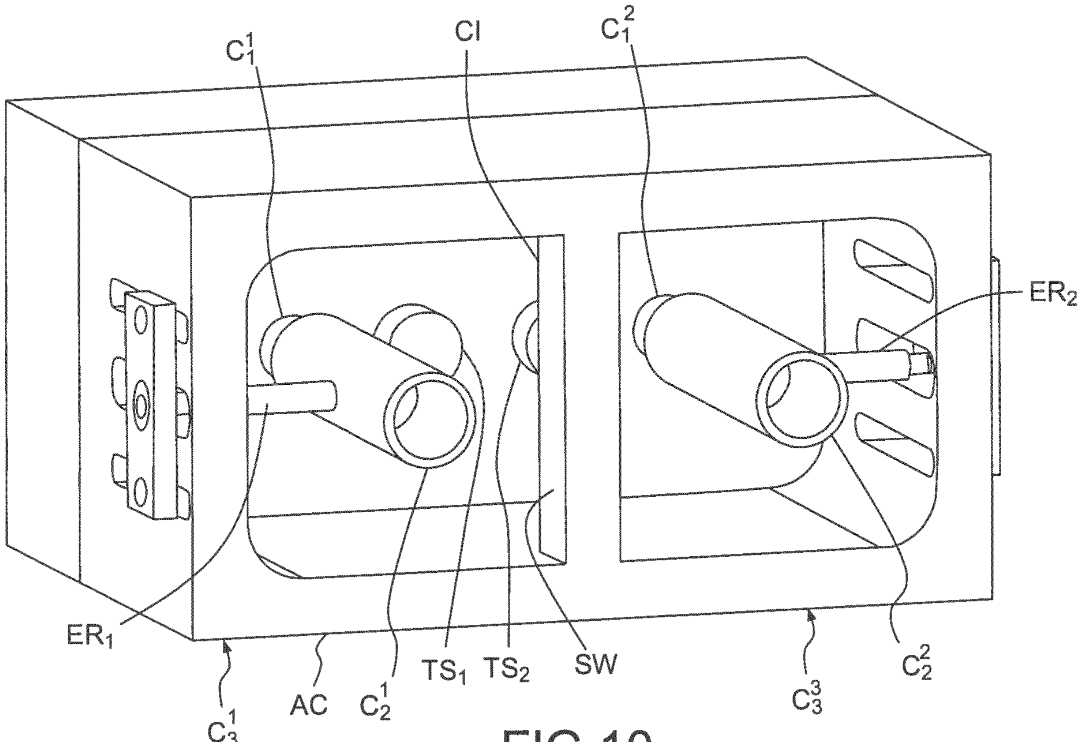

C11
CI
C12
ER2
ER1
C13
AC
C12
TS1
TS2
SW
C33
C22

FIG.10

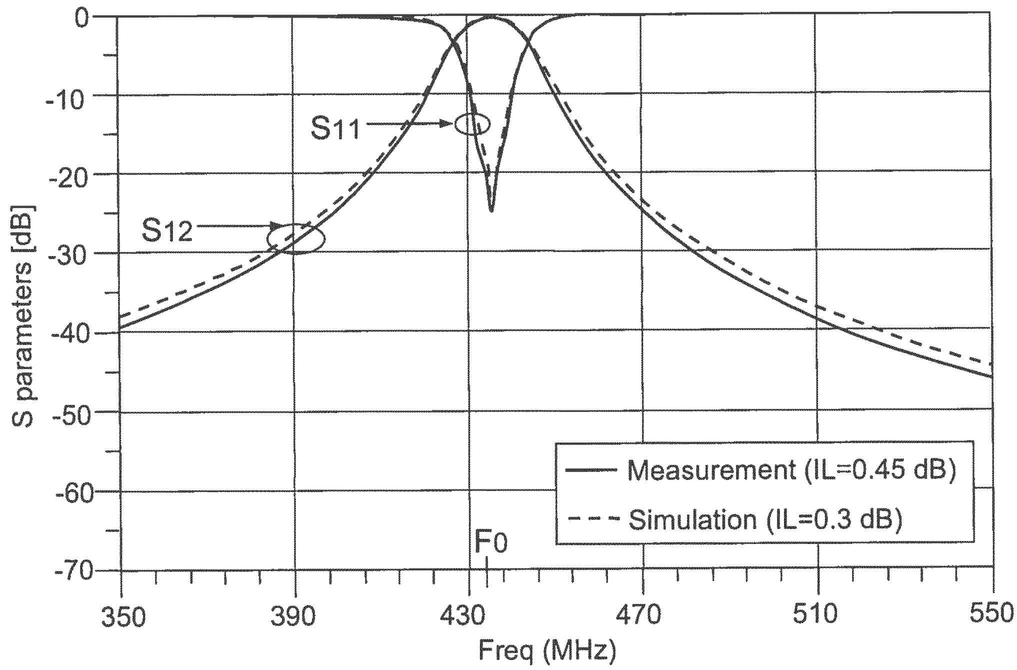


FIG.11A

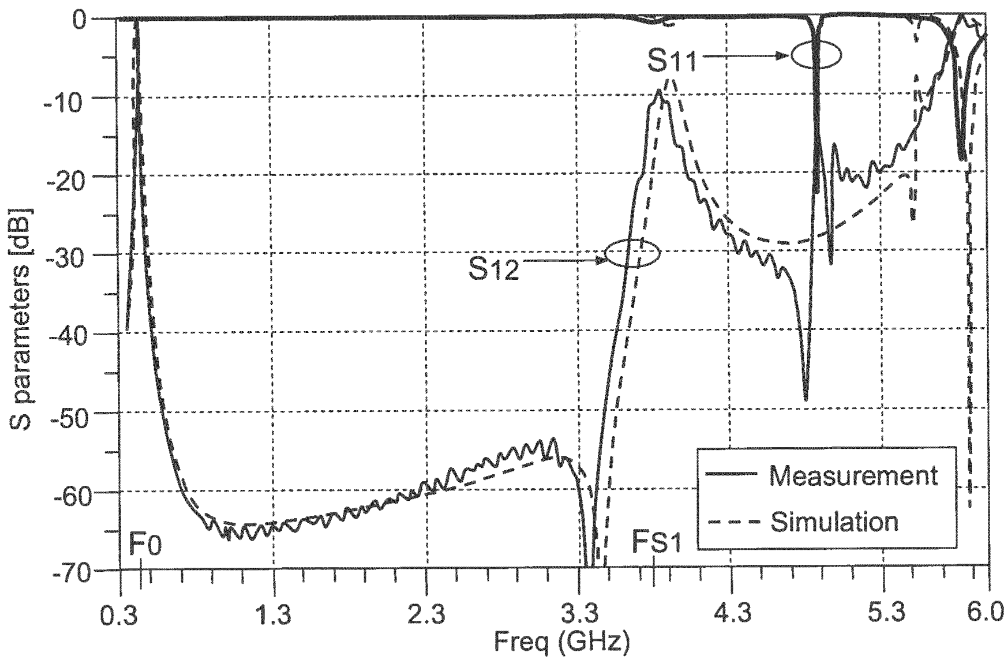


FIG.11B

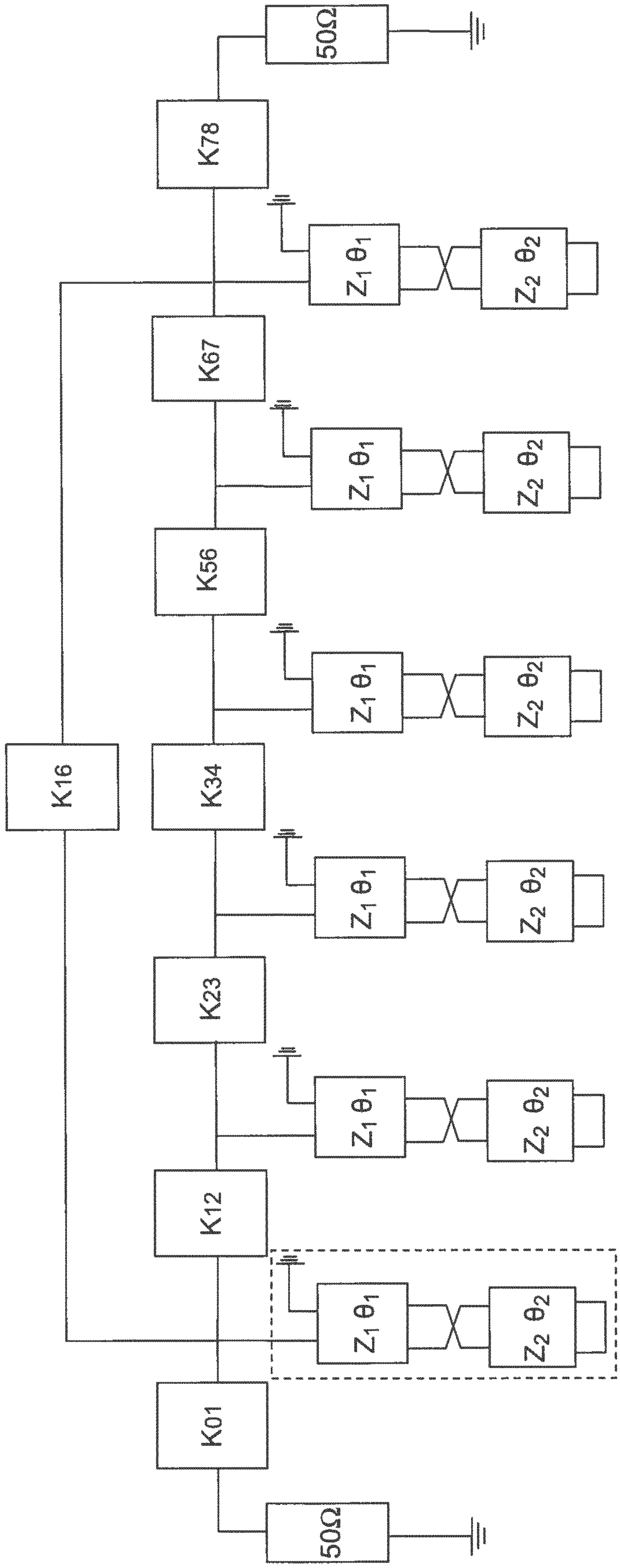


FIG.12

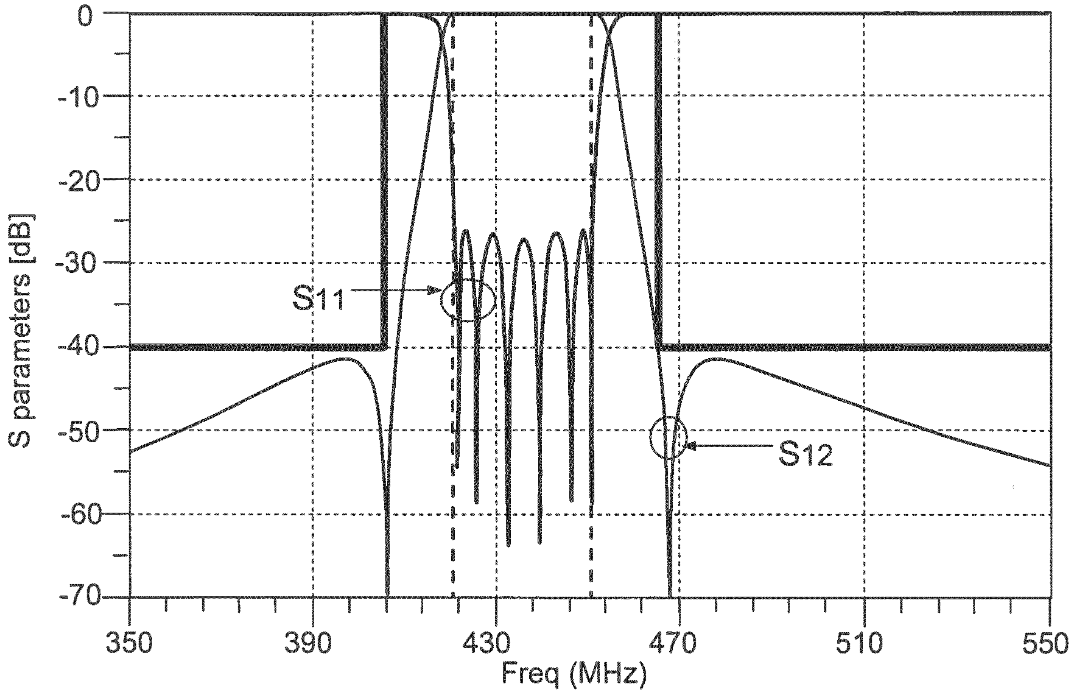


FIG.13A

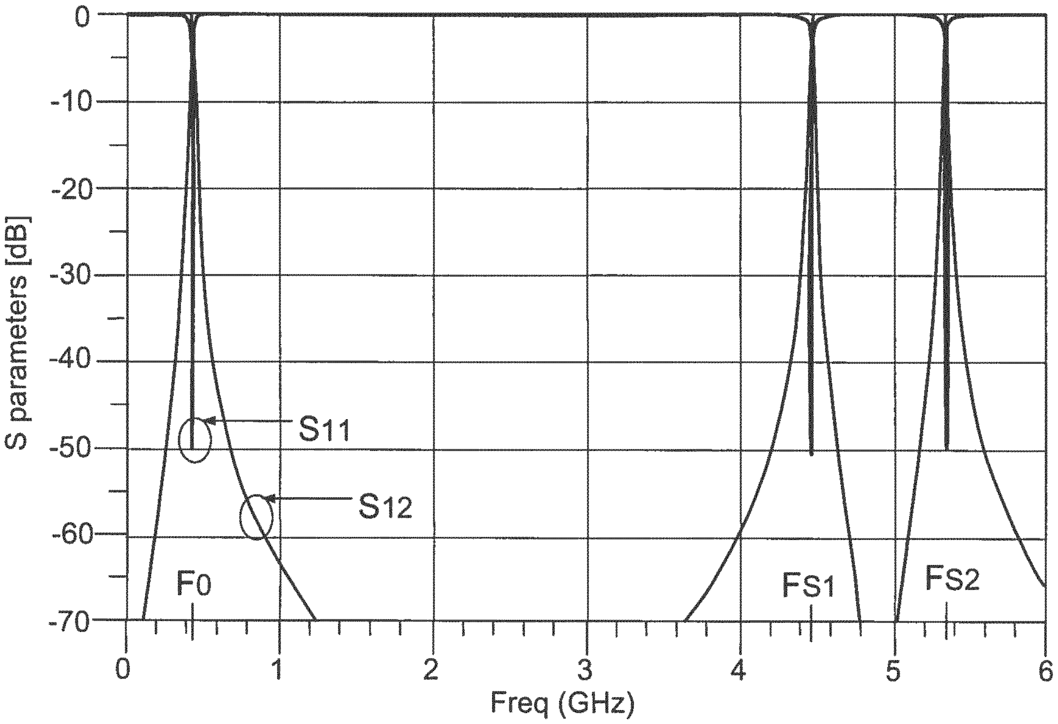


FIG.13B

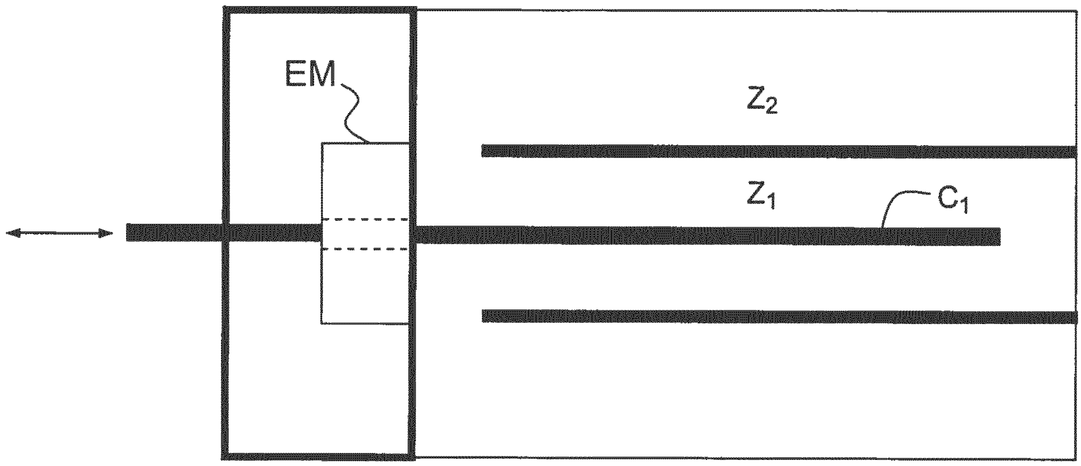


FIG.14A

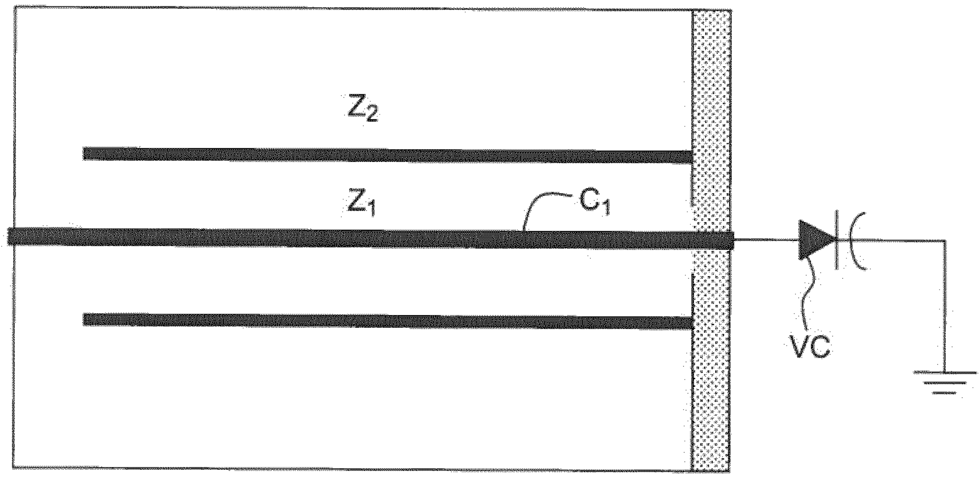
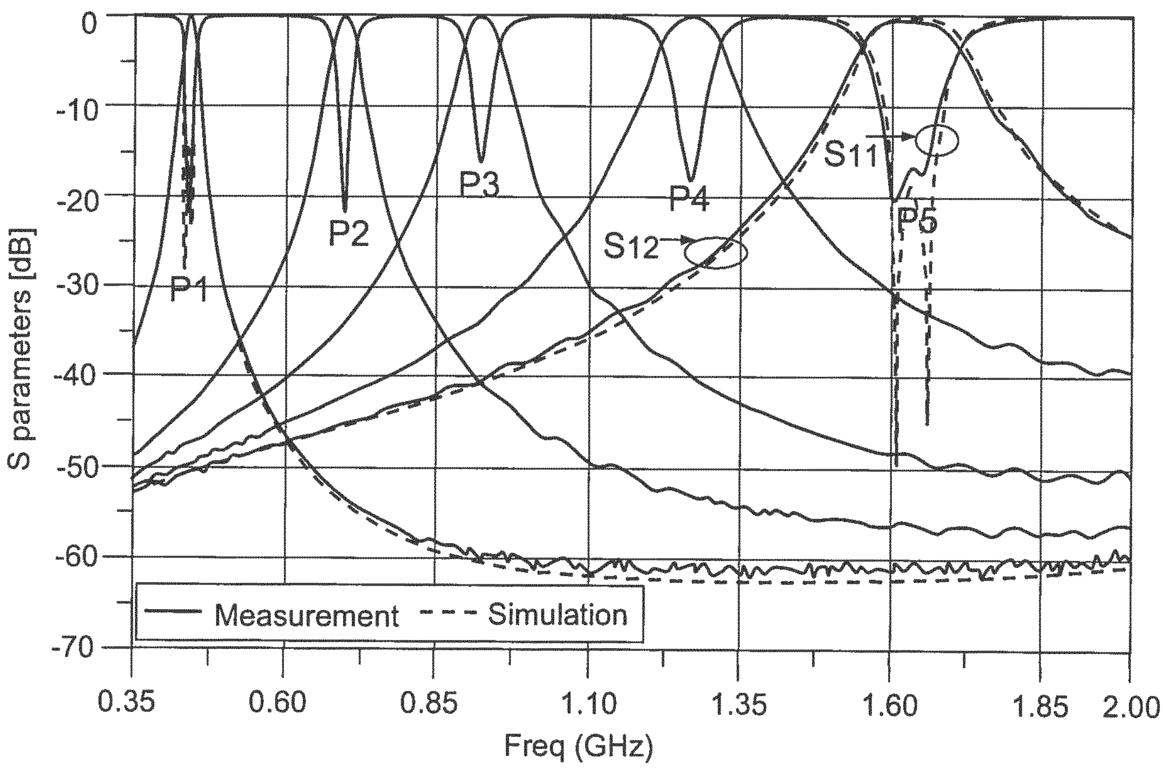


FIG.14B



0
-10
-20
-30
-40
-50
-60
-70
S parameters [dB]
P1
P2
P3
P4
P5
S11
S12
Measurement
Simulation
0.35
0.60
0.85
1.10
1.35
1.60
1.85
2.00
Freq (GHz)

FIG.15

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EUROPEAN SEARCH REPORT

Application Number
EP 13 19 6298

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
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X Y	US 2 851 666 A (ALFRED KACH) 9 September 1958 (1958-09-09) * column 4, line 48 - line 64 * * figure 5 * -----	1,3,6 7	
	-/--		

1

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
Munich	15 April 2014	Köppe, Maro

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EUROPEAN SEARCH REPORT

Application Number
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Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
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The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
Munich	15 April 2014	Köppe, Maro

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& : member of the same patent family, corresponding document

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- **S. YAMASHITA ; M. MAKIMOTO.** The Q-Factor of Coaxial Resonators Partially Loaded with High Dielectric Constant Microwave Ceramics. *IEEE Transactions on Microwave Theory and Techniques,* June 1983, vol. MTT-31 (6 **[0004]**
- **S. YAMASHITA ; M. MAKIMOTO.** Miniaturized Coaxial Resonator Partially Loaded with High-Dielectric-Constant Microwave Ceramics. *IEEE Transactions on Microwave Theory and Techniques,* September 1983, vol. MTT-31 (9 **[0004]**