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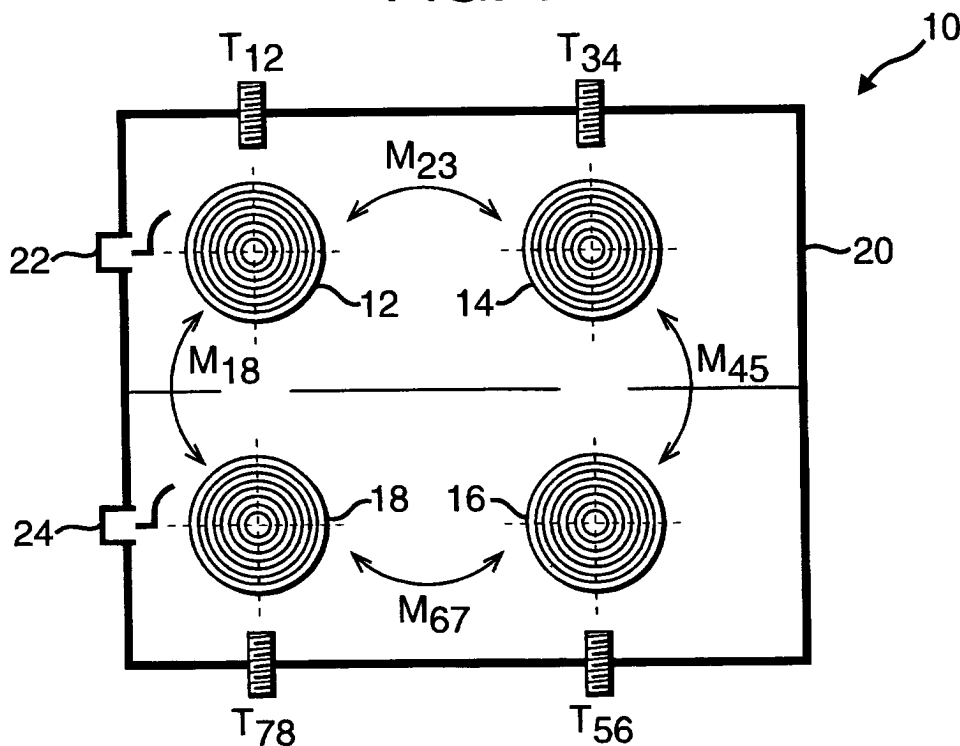
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(54) **Improved resonator filter and design method therefor**

(57) A dual mode dielectric resonator 10 comprises a plurality of dielectrics 12, 14, 16, 18, of known modes and quality factors, their intermode coupling also being

known, and a conducting enclosure 20 of known Q_d and Q_c . The modes and quality factors are calculated by deriving a mode chart for the resonator including the eigenvalues. The filter does not require an iris.

FIG. 1



Description

[0001] This invention relates to resonator filters, and to a method of designing such filters for manufacture, and for specifying existing filters.

[0002] It is known to design a dual mode filter, and to provide multiple dual mode filters coupled to each other. For example, four dual mode filters may be coupled. In such a coupling situation, at present it is usually the case that, of the eight coupling modes, only one or two will be known. In such circumstances, it is necessary to provide iris connections which require careful machining and are therefore expensive.

[0003] It is an object of the invention to provide a resonator filter in which all coupling modes are specified, and which does not require an iris.

[0004] In current filter design, resonator materials have been developed which have a high dielectric constant ϵ , a high quality factor Q , and an ultra-stable temperature coefficient of resonant frequency. For example, the barium titanate material supplied by Trans-tech, of Adamstown, MD, USA under the name Ceramic D8300 has $\epsilon=37$ and $Q=28000$. Using such a material, filters can be designed which have very low phase noise and precise frequency control and which are smaller in size than previous filters.

[0005] It is a further object of the invention to provide a yet further reduction in filter size, using a high ϵ and Q material.

[0006] According to the invention, a method of specifying a dielectric-loaded, dual mode resonator filter in a rectangular conductive enclosure is characterised by the steps of:-

computing the resonant frequency of the dielectric from known properties of the material and the dimensions of the dielectric;

deriving a mode chart of eigenvalues as a function of the wave number of the dielectric multiplied by the radius of the dielectric;

selecting a mode to match a required resonant frequency; and

deriving the unloaded quality factor of the resonator corresponding to that mode.

[0007] Also according to the invention a dual mode resonator filter comprising at least one dielectric of known modes and quality factor within a conducting enclosure of known quality factor Q_{IC} , that is, the quality factor of the conductive material taking into account the losses in the conductor. Such a filter does not require an iris.

[0008] The invention will now be described by way of example with reference to the accompanying drawings in which:-

Figure 1 is a sectional view of an 8 pole elliptic function filter; and

Figure 2 is a mode chart of a parallel plate dielectric resonator.

Figure 1 illustrates an 8 pole elliptic function filter 10 having four dielectric pucks 12, 14, 16, 18 in a rectangular metal cavity 20. There are two input/output connections 22, 24 and four tuning screws T.

[0009] The four pucks have eight coupling modes. Each tuning screw T can tune one coupling mode for each puck, shown as T_{12} , T_{34} , T_{56} , T_{78} . The couplings between the four pucks are illustrated as M_{23} , M_{45} , M_{67} , M_{18} .

[0010] There is no iris. Required couplings between the resonators can be achieved without an iris. According to the invention, all eight modes are known, as are the quality factors.

[0011] The calculation of the modes is initially based on the disclosure of D Kajfez and P Guillon, Dielectric Resonators, Oxford, MS: Vector Fields, 1990.

[0012] The solutions defined by Kajfez for each medium give four arbitrary constants for the amplitudes of the fields (two each in dielectric and air). There are four boundary conditions that must be satisfied, namely, the continuity of the tangential fields across the surface of the dielectric puck. Assuming linearity of the system, any three of the constants can be determined in terms of the fourth by using three of the four boundary conditions. That is, the characteristics of the resonator are independent of the amplitude of the wave.

[0013] The fourth boundary condition gives an equation which must be satisfied in order for a solution to exist. The continuity of the tangential field components across the surface of the each dielectric resonator shown in Fig. 1 requires

$$E_{z1} = E_{z2} \quad (1)$$

$$H_{z1} = H_{z2} \quad (2)$$

$$E_{\phi 1} = E_{\phi 2} \quad (3)$$

$$H_{\phi 1} = H_{\phi 2} \quad (4)$$

at $\rho = a$. Substituting the appropriate equations from reference 3 into equations (1-4) and eliminating the constants A , B , C and D and simplification gives the following exact condition for solution to exist:

$$F_1(x)F_2(x)=F_3^2(x) \quad (5)$$

where

$$F_1(x) = \frac{J'_m(x)}{x} + \frac{K'_m(y)J_m(x)}{\epsilon_r y K_m} \quad (6)$$

$$F_2(x) = \frac{J'_m(x)}{x} + \frac{K'_m(y)J_m(x)}{y K_m} \quad (7)$$

$$F_3(x) = \frac{\beta a m}{\kappa_0 a \sqrt{\epsilon_r}} J_m(x) \left[\frac{1}{x^2} + \frac{1}{y^2} \right] \quad (8)$$

$$\kappa_{\rho 1}^2 \triangleq \kappa^2 - \beta^2 \quad (9)$$

$$\kappa_{\rho 2}^2 \triangleq \beta^2 - \kappa_0^2 \quad (10)$$

$$x \triangleq \kappa_{\rho 1} a \quad (11)$$

$$y \triangleq \kappa_{\rho 2} a = \sqrt{(\kappa_0 a)^2 (\epsilon_r - 1) - x^2} \quad (12)$$

$$\beta a = \sqrt{(\kappa_0 a)^2 \epsilon_r - x^2} \quad (13)$$

where m is an integer, J_m and K_m are the Bessel function of the first kind and the modified Bessel function of the second kind and m^{th} orders respectively, the prime denotes differentiation with respect to the argument of the function, and $\kappa = \kappa_0 \sqrt{\epsilon_r}$ is the wave number of the dielectric, κ_0 is the wave number of free space, β is the propagation constant along the z -direction, and the real scalar permeability μ_0 , and a is the radius of the dielectric, and R_s and $\tan \delta$ are the surface resistance of the conductors, and the loss tangent of the dielectric puck, respectively.

[0014] The solution of (5) determines the values of x for which a non-trivial solution exists. Equation (5) is called the eigenvalue equation for the resonator, the zeros x of which are called the eigenvalues of the resonator.

[0015] In (12), x should not exceed a certain values x_{max} given by

$$x_{max} = \kappa_0 a \sqrt{\epsilon_r - 1} \quad (14)$$

because y then becomes purely imaginary, thereby changing the modified Bessel functions K_m into Hankel functions $H_m^{(2)}$ representing outwardly traveling waves. Hence there are only a finite number of eigenvalues for any specified m .

[0016] Another subscript n is, therefore, needed to enumerate the eigenvalues. It then becomes convenient to denote the eigenvalues by x_{mn} . The resonance condition requires

$$\beta = \frac{p\pi}{L} \quad (15)$$

where L is the length of the dielectric puck and p is an integer. Another subscript p is, therefore, needed to enumerate the resonance eigenvalues by x_{mnp} . Each set of fields (E_{mnp}, H_{mnp}) corresponding to a value of x_{mnp} is called a mode of the resonator. For $m = 0$, F_3 vanishes identically, and (5) splits into the two equations:

$$\frac{J'_1(x)}{x} + \frac{K_1(y)J_0(x)}{\epsilon_r y K_0} = 0 \quad (16)$$

and

$$\frac{J'_1(x)}{x} + \frac{K_1(y)J_0(x)}{y K_0} = 0 \quad (17)$$

[0017] Equations 16 and 17 correspond respectively, to the transverse magnetic (TM) and transverse electric (TE) fields. From (5), the eigenvalue diagram can be produced of universal nature, valid for all frequencies f and all radii a . By using (13) and (15), for a given pair of resonator dimensions a and L , the family of hyperbolas can be plotted for different values of p . Superimposing the eigenvalue diagram and the family of hyperbola curves, they intersect at a certain set of points $(x_{mnp}, (K_0 a)_{mnp})$. The resonant frequencies are then given by

$$f_{mnp} = \frac{150}{\pi a} (\kappa_0 \alpha)_{mnp} \quad (18)$$

where a is measured in millimeters.

[0018] It has now been realised that when each of four conductor-dielectric-conductor structures shown in Fig. 1 resonates as a half-wavelength resonator, three kinds of Q-factor may be obtained, due to losses in conductors, dielectric and the radiation. The total Q-factor of the resonator can be written in terms of Q_c , Q_d and Q_r as follows

$$\frac{1}{Q_0} = \frac{1}{Q_c} + \frac{1}{Q_d} + \frac{1}{Q_r} \quad (19)$$

where Q_0 is the total Q-factor of the resonator. The radiation loss (Q_r) is neglected since the resonator is enclosed by a metal package.

[0019] The conductor Q-value, Q_c , is defined as

$$Q_c = \frac{\omega W}{P_c} \quad (20)$$

[0020] The dielectric Q-value, Q_d , is defined as

$$Q_d = \frac{\omega W}{P_d} \quad (21)$$

with

$$W = W_1 + W_2 \quad (22)$$

$$P_c \Delta R_s \int_0^{2\pi} \left[\int_0^a \left(|H_{\rho 1}|^2 + |H_{\phi 1}|^2 \right) \rho d\rho + \int_a^\infty \left(|H_{\rho 2}|^2 + |H_{\phi 2}|^2 \right) \rho d\rho \right] d\phi \quad (23)$$

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$$P_d \Delta \omega W_1 \tan \delta \quad (24)$$

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$$W_1 \Delta \frac{\epsilon}{2} \int_0^{2\pi} \int_0^L \int_0^a \left[|E_{z1}|^2 + |E_{\rho 1}|^2 + |E_{\phi 1}|^2 \right] dz \rho d\rho d\phi \quad (25)$$

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$$W_2 \Delta \frac{\epsilon_0}{2} \int_0^{2\pi} \int_0^L \int_a^\infty \left[|E_{z2}|^2 + |E_{\rho 2}|^2 + |E_{\phi 2}|^2 \right] dz \rho d\rho d\phi \quad (26)$$

20

where W , P_c , P_d , W_1 and W_2 are the total peak electrical energy stored inside and outside the dielectric puck, dissipated power in the conductor thin films, dissipated power in the dielectric rod, the peak electrical energy stored inside ($\rho \leq \alpha$) the dielectric rod, the peak electrical energy stored outside ($\rho \geq \alpha$) the dielectric rod, respectively.

[0021] Inserting the appropriate equations of Kajfez into Eqs. (25), and (23) and the results into (22) and (20) and simplifications give the Q_c^{mnp} and Q_d^{mnp} for any mode excited in the resonator and can be expressed as

25

$$Q_c^{mnp} = \frac{\omega \epsilon_0 L}{4 R_s} \left\{ \frac{\epsilon_r K_m^2 [\mu_0 F_z J + M J 1] + J_m^2 [\mu_0 F_z K + M K 1]}{K_m^2 \left[\mu_0 F_z (\omega \epsilon)^2 + \left(\frac{p\pi}{L} \right)^2 \right] J 1} + J_m^2 \left[\mu_0 F_z (\omega \epsilon)^2 + \left(\frac{p\pi}{L} \right)^2 \right] K 1 \right\} \quad (27)$$

30

where

35

$$J 1 \Delta J_m'^2 + \left(1 - \left(\frac{m}{x} \right)^2 \right) J_m^2 \quad (28)$$

40

$$J 1 \Delta J_{m-1}'^2 + \left(1 - \left(\frac{m}{x} \right)^2 \right) J_{m-1}^2 - \frac{2m}{x^2} J_m^2 \quad (29)$$

45

$$K \Delta K_m'^2 - \left(1 + \left(\frac{m}{y} \right)^2 \right) K_m^2$$

50

$$K 1 \Delta K_{m-1}'^2 - \left(1 + \left(\frac{m}{y} \right)^2 \right) K_{m-1}^2 - \frac{2m}{y^2} K_m^2 \quad (31)$$

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$$M\Delta\mu_0 F_2 \left(\frac{p\pi}{L} \right)^2 + (\omega\mu_0)^2 \varepsilon F_1 \quad (32)$$

$$Q_d^{mp} = \frac{1}{\tan \delta} \left\{ 1 + \frac{J_m^2}{\varepsilon_r K_m^2} \left[\frac{\mu_0 F_2 K + MK1}{\mu_0 F_2 J + MJ1} \right] \right\} \quad (33)$$

[0022] The general expressions (27) and (33) can be simplified as a special case in which only the TE_{011} mode was considered, when the expressions given by B W Hakki, et al, "A dielectric resonator method of measuring inductive capacities in the millimetre range", IRE Trans. Microwave Theory Tech. Vol. MTT-8, pp. 402-410, July 1960 and by Z-Y Shen, et al, "High T_c Superconducting-Sapphire Microwave Resonator with Extremely High Q-Values up to 90 K", IEEE Trans. Microwave Theory Tech. Vol. MTT-40, No.12, pp. 2424-2432, Dec. 1992 will be reached.

[0023] Equations 27 and 33 allowed derivation of the energy stored and the energy loss in, respectively, the conductor and the dielectric; thus precise information is available on all modes of the dielectric and the conductive material of which the cavity is made.

[0024] To determine the zeros of the transcendental equation above, (Eqn 5) a combination of bisection, secant, and inverse quadratic interpolation methods have been used. The first few eigenvalues have been computed versus Koa and shown in the Fig. 2 for $\varepsilon_r = 37$.

[0025] The curves in Fig. 2 describe the change of eigenvalues as functions of the normalised frequency Koa for the five higher order modes. In Fig.2 the eigenvalues vary with frequency in contrast to those of the metallic cylindrical waveguide filled with the uniform dielectric material.

[0026] Fig. 2 can be used to determine the wavelength of any mode among the modes shown. As shown in Fig. 2, the eigenvalues are slowly varying functions of Koa which can be fitted by simple polynomials.

[0027] Also, Fig. 2 allows a graphical procedure to be used for the determination of the resonant frequencies of the resonator. The families of curves shown in Fig. 2 are obtained by using the above equations for different values of p .

[0028] Prediction and identification of the various modes of the resonator can be made from Fig. 2. The advantage of this method is that one can easily recognise the order in which resonant frequencies of various modes will appear. For given radius a and length L , the abscissa Koa increases linearly with frequency.

[0029] Hence, one can see that the lowest resonant frequency belongs to the HEM_{111} resonance, the next higher is TE_{011} , etc. From Fig. 2 each resonant mode is obtained by using the relevant hyperbola and noting the intersection with the eigenvalues of various modes.

[0030] In summary, a filter of known materials is characterised by deriving a mode chart, from the chart reading off the mode of the required frequency, and calculating Q_c and Q_d that mode from Equations 27 and 33. If Q is insufficiently high, the dimensions of the puck are altered and the calculation is re-run. Once the resonator dimensions and modes are known, coupling between the resonators can be calculated from Equations 27 and 33. The calculations can be applied to filters during the manufacturing process, or can be applied to existing filters which can then be more fully specified, and can be used without an iris.

[0031] It has also been found that lower midband insertion losses are achievable, in comparison with filters having an iris, because conduction currents on the metallic cavity ends can be eliminated.

[0032] One material suitable for use as the dielectric is the barium titanate material Ceramic D8300 referred to above, and the cavity may be made of copper. Filters designed according to the invention using Ceramic D8300 can be of reduced size by a factor of 12 in comparison with air filled cavity resonators using other materials.

[0033] Filters according to the invention are applicable as low-loss microwave filters in mobile communication bands in base stations for GSM (Global System for Mobile Communications).

[0034] In a variation as described in our co-pending application no. filed on even date the tuning screws can be dispensed with as well as the iris.

Claims

1. A method of specifying a dielectric-loaded, dual mode resonator filter in a rectangular conductive enclosure is characterised by the steps of :

computing the resonant frequency from known properties of the materials of the dielectric and the enclosure and their dimensions;

deriving a mode chart of eigenvalues as a function of the wave number of the dielectric multiplied by the radius of the dielectric;
selecting a mode to match a required resonant frequency; and
deriving the unloaded quality factor of the resonator corresponding to that mode.

- 5
2. A method according to Claim 1 in which the modes transverse electric TE, transverse magnetic TM and hybrid electromagnetic HEM are derived.
- 10
3. A method according to Claim 2 in which the five higher coupling modes HEM_{111} , TE_{011} , TM_{011} , HEM_{311} and TM_{021} , are derived.
- 15
4. A method according to any one of Claims 1, 2 and 3 applied to at least two dielectric filters in a single rectangular enclosure, further comprising the additional step of calculating the coupling between modes of the at least two filters.
- 20
5. A dual mode resonator filter comprising at least one dielectric of known modes and quality factor within a conducting enclosure of known Q_d and Q_c as herein defined.
6. A resonator according to Claim 5 comprising at least two dielectrics of known modes and quality factors, all of the couplings between the modes also being fully specified.
7. A resonator according to Claim 6 in which the dielectric is barium titanate.

FIG. 1

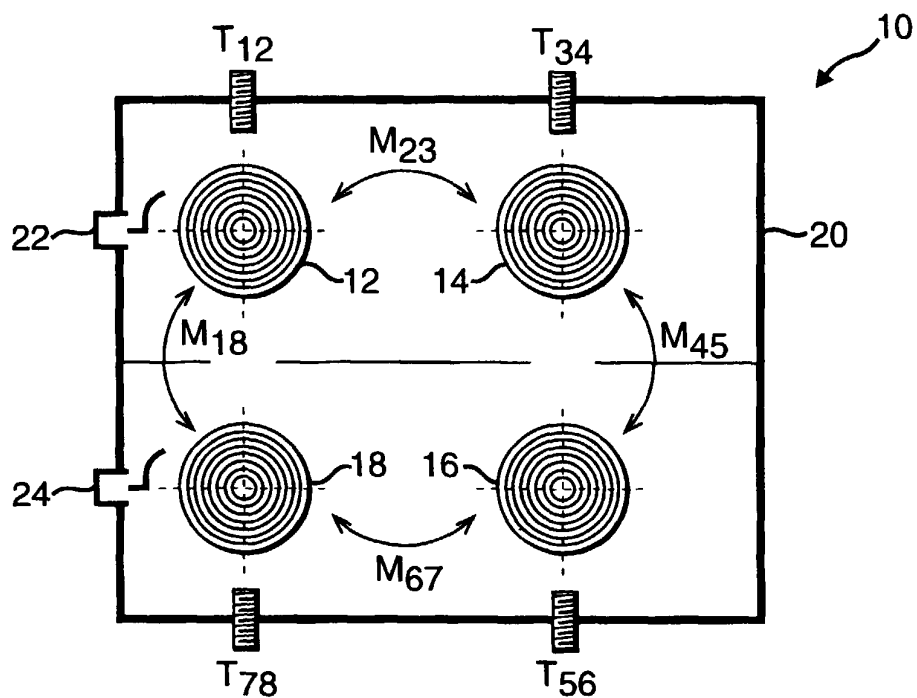
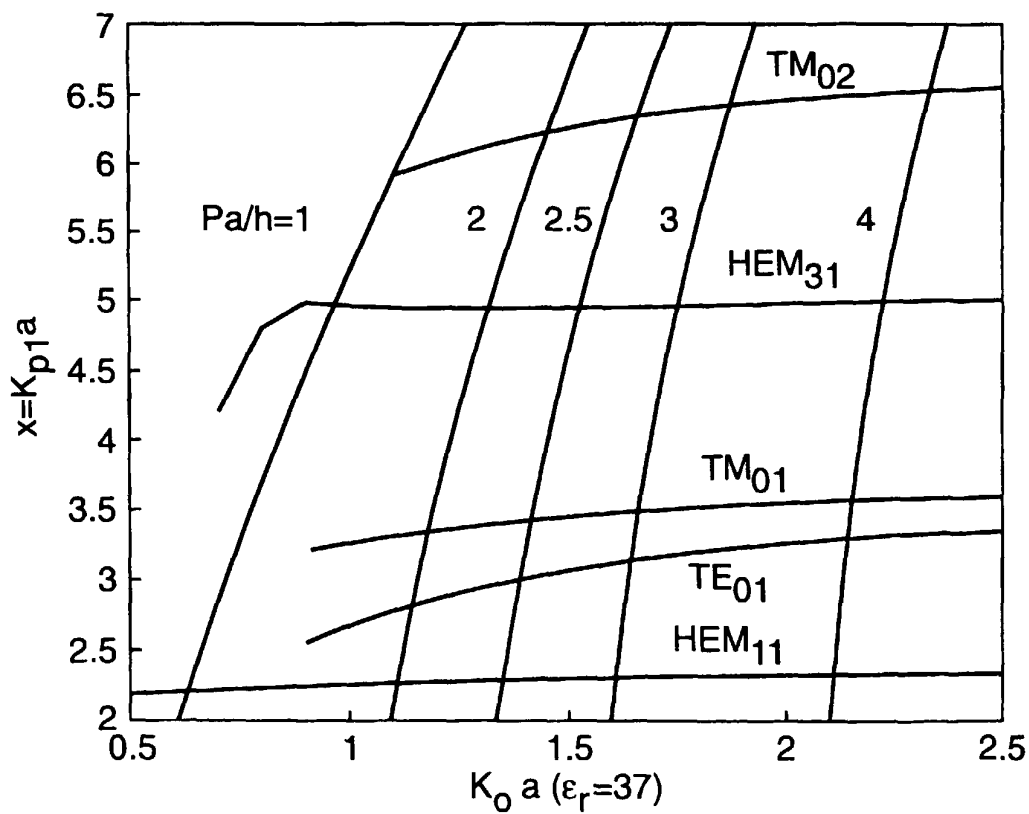


FIG. 2





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EUROPEAN SEARCH REPORT

Application Number
EP 99 30 8220

DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.7)
A	D. KAJFEZ ET AL.: "TUBULAR DIELECTRIC WAVEGUIDES AND RESONATORS" 1988 IEEE SOUTHEASTCON-CONFERENCE PROCEEDINGS, 11 - 13 April 1988, pages 566-570, XP002133233 KNOXVILLE (US) * page 566, left-hand column, line 38 - page 567, right-hand column, line 18; figures 1,6 *	1-3	H01P1/208 H01P7/10
A	ZHONG-MIN ET AL: "TRIPLE-MODE DIELECTRIC RESONATOR LOADED CAVITY1" MTT-S INTERNATIONAL MICROWAVE SYMPOSIUM DIGEST,US,NEW YORK, IEEE, vol. -, 10 - 14 June 1991, pages 687-690, XP000260445 BOSTON (US) * page 687, right-hand column, line 1 - page 689, left-hand column, line 4 *	1	
			TECHNICAL FIELDS SEARCHED (Int.Cl.7)
			H01P
The present search report has been drawn up for all claims			
Place of search THE HAGUE		Date of completion of the search 16 March 2000	Examiner Den Otter, A
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