United States Patent

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[54] **MICROWAVE DEVICES**

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[51] **Int. Cl.**.....**H03h 7/10,** H03h 13/00, C04b 35/48

[58] **Field of Search**..106/39 R, 46; 252/520; 333/73, 333/73 W, 84 M

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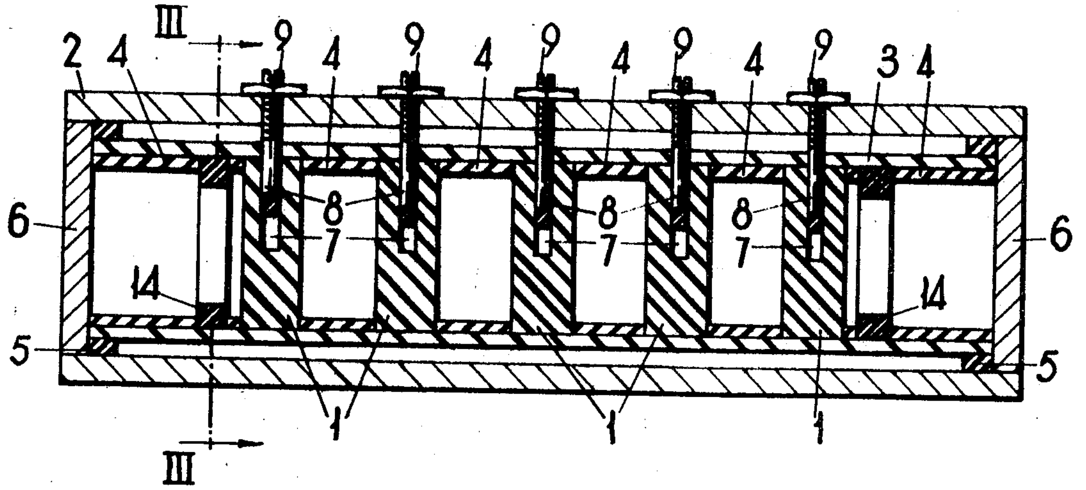
[57] **ABSTRACT**

In a microwave device incorporating a component formed of dielectric material, and so designed that the response of the device is dependent on the permittivity of the said material, the component is formed of a ceramic material consisting essentially of one or more alkaline earth metal zirconates, or zirconates and titanates, the composition of the material being such that the atomic ratio of zirconium to titanium is not less than 80 : 20, that it does not contain more than 10 mole percent of barium titanate, and that the material will have, at frequencies in the range of 400 MHz to 30 GHz, permittivities in the range of 25 to 75, a substantially constant temperature coefficient of permittivity, which is preferably within the range from +50 to −100 p.p.m. per degree Centigrade, and a loss tangent not exceeding 0.005 at 20° C. The dielectric materials are suitable for use, for example, as resonators for microwave bandpass filters, and as substrates for microwave integrated circuits, and are advantageous for these applications in having substantially constant temperature coefficients of permittivity, of controllable values, as well as low dielectric losses, at microwave frequencies.

3 Claims, 5 Drawing Figures



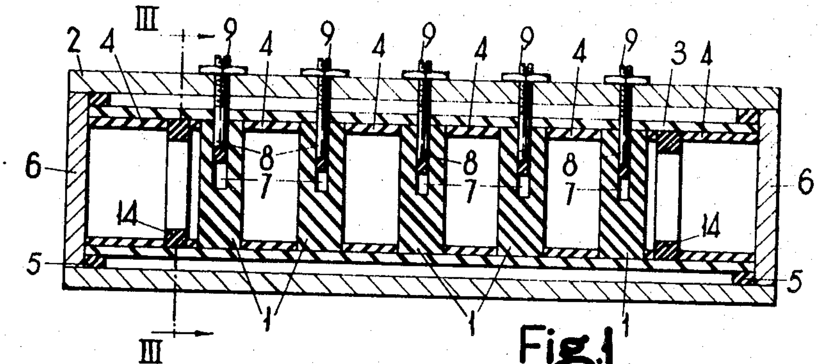


Fig.1

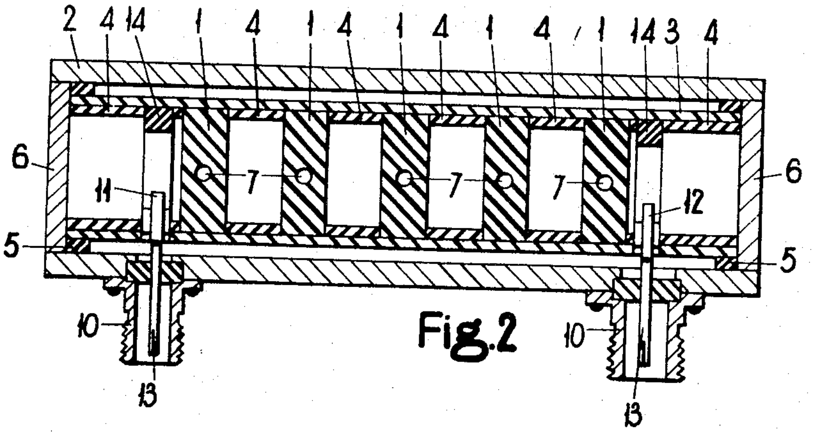


Fig.2

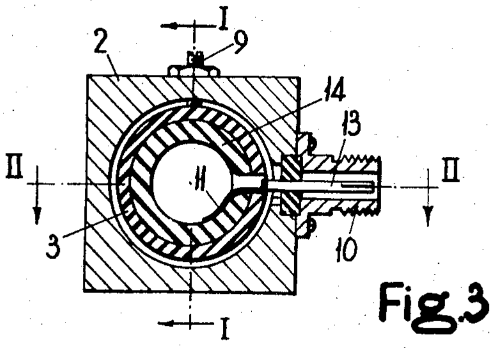


Fig.3

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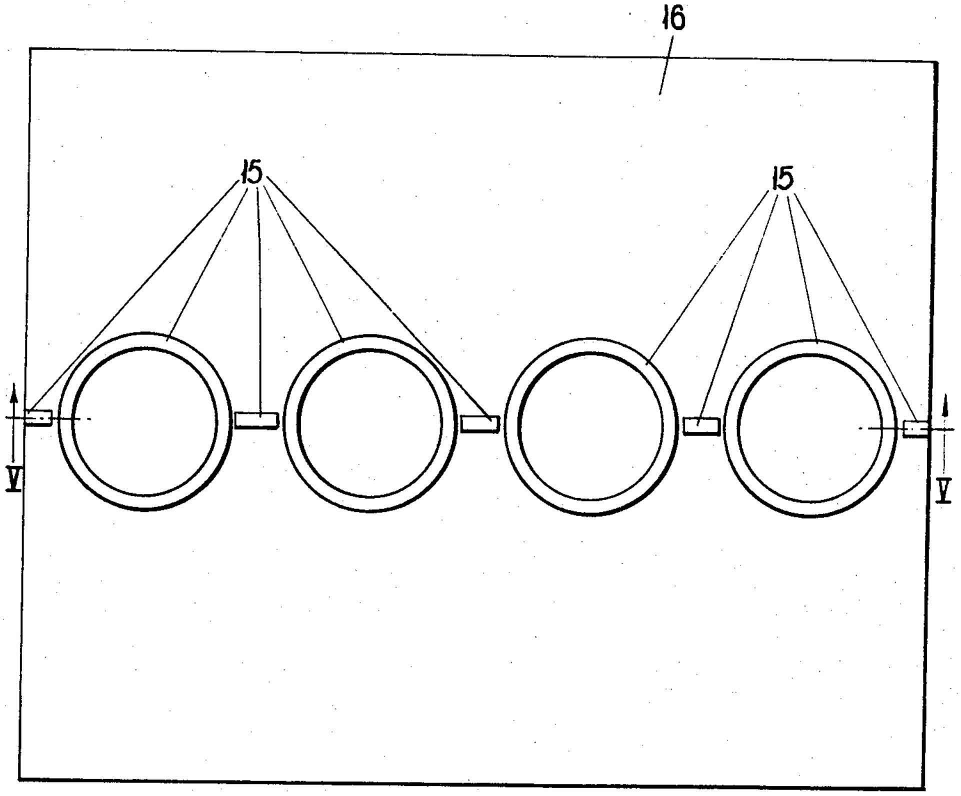

Fig.4

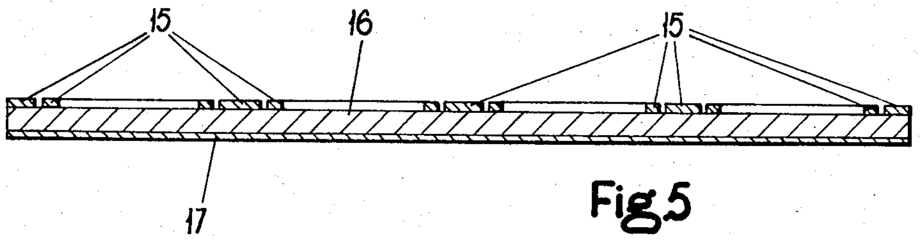

Fig.5

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MICROWAVE DEVICES

This invention relates to electrical devices of the kind designed for operation at microwave frequencies, that is to say at frequencies in the range of 400 MHz to 30 GHz, for use for example in telecommunications equipment, and incorporating components formed of dielectric materials, wherein the response of the device is dependent on the permittivity of the dielectric material.

It is an object of the invention to provide improved microwave devices of the kind referred to incorporating components formed of dielectric materials of a particular class which, as well as having permittivities within a suitable range of values at microwave frequencies, also have at such frequencies controlled, substantially constant temperature coefficients of permittivity and low loss tangents.

According to the invention, in a microwave device incorporating a component formed of dielectric material, and so designed that the response of the device is dependent on the permittivity of the said material, the said component is formed of a ceramic dielectric material consisting of at least one compound of the general formula ABO_3, where A is a metal of the group consisting of barium, strontium and calcium and B is a metal of the group consisting of zirconium and titanium, the composition of the material being so chosen that the atomic ratio of zirconium to titanium is in the range of 80 : 20 to 100 : 0, that it does not include significant amounts of both barium and titanium and that the material will have, at frequencies in the range of 400 MHz to 30 GHz, permittivities in the range of 25 to 75, a substantially constant temperature coefficient of permittivity, and a loss tangent not exceeding **0.005** at **20°** C.

The temperature coefficient of permittivity of the dielectric material is usually preferred to be within the range from + 50 to −100 p.p.m. per degree Centigrade. In some cases this coefficient may be required to have a specific positive or negative value to compensate for some other feature of the device, for example for the coefficient of thermal expansion of a metal component. In other cases, however the composition of the material may be balanced to give a value of, or near, zero for the temperature coefficient of permittivity.

The permittivity and loss tangent of a given dielectric material will of course vary to some extent with variations in the frequency at which the device in which it is incorporated is operated, the permittivity decreasing in steps with increasing freqency, and peaks in the loss tangent occurring at the relaxation frequencies, that is to say at the frequencies at which the step-wise drops in the permittivity occur.

Since the values of the permittivity and loss tangent of barium titanate are considerably higher than the limiting values specified above, and since moreover this substance has a very variable temperature coefficient of permittivity, the dielectric materials employed in accordance with the invention should not contain large amounts of barium titanate. It will thus be understood that the above proviso that the dielectric material does not include "significant amounts of both barium and titanium" means that, whilst a considerable proportion of either barium or titanium may be present if desired, if one of these elements is present there should not be a sufficient amount of the other one to make it possible for barium titanate to be formed in such a proportion as to cause the specified limits of permittivity and loss tangent, for the material as a whole, to be exceeded. The proportion of barium titanate which can be tolerated in any given material will of course depend upon the composition, and consequent properties, of the other constituent of constituents of the material, but should not in any case exceed **10** mole percent of the material.

In some cases the dielectric material may consist of a single compound of the class referred to, provided that such compound possesses the required properties: calcium zirconate is an example of a compound which can be used alone in this way. In other cases the dielectric material will consist of a mixture or solid solution of at least two compounds each of which is of the general formula ABO_3 as defined above. Thus suitable dielectric materials can be formed from mixtures of titanates and/or zirconates individually having low loss tangents and temperature coefficients of permittivity of opposite sign, the relative proportions of the individual compounds being adjusted as required to give a dielectric material having a permittivity within the specified range and a temperature coefficient of permittivity of zero or of a desired positive or negative value. Suitable combinations of compounds are, for example, barium zirconate and strontium zirconate, barium zirconate and calcium zirconate, strontium titanate and strontium zirconate, and calcium titanate and calcium zirconate.

The barium and strontium compounds referred to all have the cubic perovskite crystal structure and form single phase solid solutions with one another. The calcium compounds, however, have an orthorhombic perovskite crystal structure and form solid solutions with the barium or strontium compounds only over limited ranges of composition which do not include materials with the high calcium zirconate content necessary to give low temperature coefficients of permittivity. Since a material consisting of a single phase solid solution is more readily reproducible than a material consisting of a mixture of compounds, it is in general preferred to employ combinations of barium-barium, strontium-strontium, or barium-strontium compounds, without calcium compounds, except for any particular applications for which the presence of a calcium compound imparts desirable properties to the dielectric material; similarly combinations of calcium-calcium compounds will usually be preferred without barium or strontium compounds.

Some preferred dielectric materials for use in accordance with the invention are barium strontium zirconates in which the atomic ratio of barium to strontium is in the range of 40 : 60 to 80 : 20, calcium titanate-zirconates in which the atomic ratio of titanium to zirconium is in the range of 0 : 100 to 5 : 95, and strontium titanate zirconates in which the atomic ratio of titanium to zirconium is in the range of 2 : 98 to 8: 92. One particular material which is especially advantageous for some applications, since its temperature coefficient of permittivity is near zero, is barium strontium zirconate containing barium and strontium in the atomic ratio of 56 Ba : 44 Sr. The calcium-containing materials tend to have increased losses and variable temperature coefficients of permittivity in the presence of moisture: it may therefore be necessary to ensure that moisture is excluded from these materials during use.

One example of a device in accordance with the invention is a microwave bandpass filter incorporating one or more dielectric resonators in the form of bars, cylinders or discs of dielectric material as specified above, in replacement for the metal waveguide resonator incorporated in a conventional microwave filter. A metal resonator is disadvantageous in a microwave device since it is physically large, being the length of half a wavelength in air: replacement of the metal resonator by a dielectric resonator enables the size of the resonator to be reduced, since the wavelength, varying inversely as the square root of the permittivity of the dielectric, is considerably smaller in the ceramic dielectric than in air. In use, a ceramic dielectric resonator is usually placed within a metal screen, which results in a slight increase in the resonant frequency of the dielectric element. It has been proposed to use resonators formed of titanium dioxide, but this material has a very high temperature coefficient of permittivity (nearly −1,000 p.p.m./° C.), which makes it unsuitable for this application.

The use of dielectric materials composed of zirconates or titanates and zirconates as aforesaid as resonators in microwave filters in accordance with the invention, is advantageous by virtue of the temperature stability of permittivity, and hence temperature stability of resonant frequency, of these materials. For example, a resonator composed of barium strontium zirconate ceramic of the composition $(Ba_{0.55}Sr_{0.45}ZrO_3$ will give frequency stability of $10^{-5/\circ}$ C., that is to say a frequency drift of only approximately 20 kHz/ ° C. for a resonant frequency of 2 GHz. Hence the use of dielectric resonators in accordance with the invention makes it feasible to design filters having band widths as small as 20 MHz for operation over a temperature range of, for example, 0° to 50° C. Furthermore a reduction in size, compared with conventional filters having resonant cavities, of at least 2 : 1 in all linear dimensions can be obtained. As examples of specific applications, a dielectric material having a loss tangent of 0.002, with a corresponding Q-factor of 500, is suitable for use as a resonator in a broad band filter, and a material having a loss tangent of 0.0002, which will give a Q-factor of 5,000, will be acceptable as a resonator in a narrow band filter.

Another type of device in which the aforesaid dielectric materials can be employed with advantage is an integrated microwave circuit, the dielectric material being used to form the substrate carrying the conducting strips constituting the circuit elements. It has been proposed to use high density alumina for this purpose, but the temperature stability of permittivity of alumina is not as good as is required for many applications, and it would be desirable to use materials having higher permittivities than that of alumina (9.5), especially at the lower microwave frequencies, below 3 GHz, at which the wavelength in alumina exceeds 10 cm. The dielectric materials employed in accordance with the invention are advantageous in this connection, since their compositions can be selected so as to have lower temperature coefficients of permittivity than that of alumina, and since they also have higher permittivities than that of alumina, enabling the wavelength in the material, at a given frequency, to be almost halved in comparison with that in alumina.

The dielectric materials for use in the devices of the invention can be prepared by techniques conventionally employed for the production of ceramic dielectric materials of this type, that is to say by preparing an intimate mixture of suitable powdered starting materials in the required relative proportions, pressing the mixture, and heating the pressed compacts to effect reaction and sintering. The materials can be prepared from mixtures of the requisite pre-formed compounds of the formula ABO_3 as defined above, but preferably the starting mixture comprises the constituent oxides and/or compounds, such as carbonates or hydroxides, which decompose on heating to give the oxides.

A preferred procedure for preparing these materials, by which ceramic bodies of density approaching the theoretical density, and hence having optimum permittivity, can be obtained, includes the steps of isostatically pressing the starting mixture to form compacts of simple shapes, such as rods, prefiring the compacts at a sufficiently high temperature to effect partial sintering, sufficient to form a coherent body, crushing the prefired compacts to powder, die-pressing the powder to form compacts of the desired shapes of the components to be produced, and firing these compacts at a temperature higher than that employed for the prefiring step, to convert them into dense, sintered ceramic bodies.

For some applications, it may be necessary to reproduce the particular properties required (for example zero temperature coefficient of permittivity or a specific value of such coefficient) more accurately than is possible by direct repetition of a standard preparation procedure, in which there is usually a small margin of error. Either of the following procedures may then be used.

In the first procedure for accurate reproduction of properties, prefired compacts of three slightly different compositions are formed and crushed to powder in the usual way. One of these compositions is nominally the preferred composition for obtaining the desired properties, and the other two compositions depart from the preferred composition in opposite directions (for example one may contain a small excess of zirconia while the other is deficient in zirconia to the same extent) to give properties which deviate in opposite directions from the required properties. A small sample of every batch of prefired and crushed powder so formed is pressed and sintered, and the properties of the sintered products are measured. Any deviation from the required properties in the sintered sample of a particular batch of the nominally preferred composition is then corrected by the appropriate addition to this batch of a small quantity of powder from a batch of one of the other compositions.

In the second procedure for accurate reproduction of properties, the nominally preferred composition is not made and used, only the two compositions which depart from the preferred composition in opposite directions being used. Again, the properties of each batch of prefired, powdered material are determined by sintering and measuring small samples. The powders of the two compositions are then mixed in the appropriate proportions for the particular batches used to give the required properties.

A specific method which we have employed for the production of components formed of some of the dielectric materials referred to will now be described by way of example.

The materials which we have prepared by the method of the example were as follows:

A. Barium strontium zirconates, with atomic ratios of Ba : Sr ranging from 0.5 : 0.5 to 0.7 : 0.3;

B. barium calcium zirconates, with atomic ratios of Ba : Ca ranging from 0.3 : 0.7 to 0.05 : 0.95;

C. calcium zirconate-titanates, with atomic ratios of Zr : Ti ranging from 0.935 : 0.065 to 0.987 : 0.013;

D. calcium zirconate, $CaZrO_3$;

E. strontium zirconate-titanates, with atomic ratios of Zr : Ti ranging from 0.94 : 0.06 to 0.988 : 0.012.

The above materials were prepared from the following starting materials, all in powder form, in the appropriate relative proportions to give the respective compositions required:

A. Barium carbonate, strontium carbonate, and zirconium dioxide;

B. barium carbonate, calcium carbonate, and zirconium dioxide;

C. calcium carbonate, zirconium dioxide, and titanium dioxide;

D. calcium carbonate and zirconium dioxide;

E. strontium carbonate, zirconium dioxide, and titanium dioxide.

In each case, the mixture of powdered starting materials was milled with water in a porcelain ball mill for 36 hours, then the milled mixture was dried and compacted into rods by hydrostatic pressure of 7 tons per square inch, and the rods were prefired in air at 1,250° C. for 2 hours. The prefired rods were crushed in a disc mill, and the resulting powder was milled with water (or in one case, with acetone) in a ball mill for 24 hours. The powder was then dried, mixed with solution of 2 wt. percent camphor in ether, and either die-pressed in the form of discs under a pressure of 9 tons per square inch, or isostatically pressed in the form of rods under a pressure of **12** tons per square inch. The discs or rods were finally fired in air at 1,450° C. for 2 hours to convert them to dense, sintered ceramic material.

The compositions of a number of materials which have been prepared by the method of the example are listed in the following Table, together with the values of some of the properties of these materials which have been determined at an audio frequency of 1.6 kHz and at a microwave frequency of 5 GHz, the properties being the permittivities and loss tangents at both frequencies, the temperature coefficient of capacitance at audio frequency, and the temperature coefficient of resonant frequency at microwave frequency. Audio frequency measurements were carried out, as well as microwave frequency measurements, in most cases, because knowledge of the audio frequency properties of a material is of value in giving an indication of the properties the material will possess at microwave frequencies, and audio frequency measurements are more easily made.

The temperature coefficients of permittivity of the materials were not determined directly, but can readily be deduced from the temperature coefficient of capacitance, or from the temperature coefficient of resonant frequency of a microwave cavity containing a disc of the material, which properties are more conveniently measured at audio frequency and microwave frequency respectively. Thus the temperature coefficient of permittivity is derived from the temperature coefficient of capacitance by subtracting from the latter the coefficient of thermal expansion of the material, which for these ceramic materials is only 8 - 10×10^{-6}/° C., or is derived from the temperature coefficient of resonant frequency by solving the resonator equations as given by S.B.Cohn and K.C. Kelly in an article published by the Institute of Electrical and Electronics Engineers, in the Transactions on Microwave Theory and Techniques, Volume **14** (1966), page 406. In practice, the important temperature coefficient for microwave applications is that of the resonant frequency (which can be measured) rather than that of the permittivity (which must be calculated). The resonant frequency is related to E^{-} , where E is the permittivity, and the temperature coefficient of resonant frequency is related to — one-half times the temperature coefficient of permittivity. It is therefore expected that if the temperature coefficient of permittivity is small, that of resonant frequency will also be small, and if the temperature coefficient of permittivity is large, that of resonant frequency will be large and of opposite sign.

For carrying out the measurements of the properties referred to, at audio frequency, the major faces of the sintered discs of the non-metallized prepared as described above, were lapped to produce flat parallel surfaces and silver paste was applied to these surfaces, dried at 120° C. for 12 hours and fired at **650**° C. for 1 hour. The measurements of microwave properties were carried out on non-metallised discs at a frequency close to 5 GHz, the temperature coefficients of resonant frequency being determined for such discs 20 mm in diameter and 4 mm thick, resonanted in the TE_{011} mode in a closely fitting waveguide reflection cavity cut-off in the air regions.

In preparing some of the materials listed in the Table, minor modifications were made in the procedure described in the above example, as follows:

Compositions 3 and 4 were 2.5 mol.% deficient in ZrO_2; in preparing composition 5 the prefired powder was milled in acetone instead of in water; and in preparing composition 12 the prefire was carried out at **1,350**° C. instead of at 1,250° C.

The abbreviations "TCC" and "TCF" employed in the column headings in the Table mean respectively "-temperature coefficient of capacitance" and "temperature coefficient of resonant frequency."

TABLE

	Properties at frequency 1.6 kHz			Properties at frequency 5 GHz		
Composition (ABO_3 compound(s))	$10^6 \times$TCC per ° C. (± 15 error)	Permittivity at 20° C.	$10^4 \times$loss tangent at 100° C.	$10^6 \times$ TCF per ° C.	Permittivity at 20° C.	$10^4 \times$loss tangent at 20° C.
$Ba_xSr_{1-x}ZrO_3$:						
1 x=0.70	−45	39.0	5	−5.8		
2 x=0.60	−22	38.2	19			

TABLE –Continued

Composition (ABO_3 compound(s))	Properties at frequency 1.6 kHz			Properties at frequency 5 GHz		
	$10^6\times$TCC per ° C. (± 15 error)	Permittivity at 20° C.	$10^4\times$loss tangent at 100° C.	$10^6\times$ TCF per ° C.	Permittivity at 20° C.	$10^4\times$loss tangent at 20° C.
3 $x=0.50$	+15	36.8	11	−21.9		
4 $x=0.55$	+5	37.6	40		34.8	15
5 $x=0.56$	0	38.1	11	−17.6	34.7	18
$CaZr_xTi_{1-x}O_3$:						
6 $x=0.935$	−129	36.7	20			
7 $x=0.96$	−59	34.7	95	+4.7	31.5	4.0
8 $x=0.987$	−17	32.9	3	+6.6	30.3	2.5
9 $CaZrO_3$	+33	32.0	60		28.0	7.6
$SrZr_xTi_{1-x}O_3$:						
10 $x=0.94$	−52	37.8	<5		34.8	9.2
11 $x=0.955$	0	36.1	<3	−21.1	33.4	7.0
12 $x=0.955$	0	36.0	<3	−15.0	33.1	
13 $x=0.965$	+32	35.4	12	−30.2	32.7	8.1
14 $x=0.988$	+93	33.2	25			

It is apparent from the figures given in the above Table that, for the barium strontium zirconates and the strontium zirconate-titanates, the value of the sum of TCF and one-half TCC is within the range from -13×10^{-6} /° C. to -25×10^{-6}/° C. Thus to obtain a zero temperature coefficient of resonant frequency at microwave frequencies, with discs of these materials of the dimensions referred to above and resonant in the TE_{011} mode, a temperature coefficient of capacitance at audio frequencies of approximately -40×10^{-6}/° C. is required. The audio frequency figures also show that a temperature coefficient of capacitance approaching zero can be obtained by suitable adjustment of the composition of each class of material, and therefore indicate that a temperature coefficient of resonant frequency approaching zero at microwave frequencies can also be obtained by adjusting the compositions so as to produce the required changes in the values shown. Moreover, the temperature coefficient of permittivity at microwave frequencies in some of the cases listed is only slightly negative, so that little adjustment of the composition would be required in these cases.

The temperature coefficients of the calcium zirconate-titanates do not follow the relationship given above for the other classes of compounds listed in the Table: the temperature coefficients of these calcium compounds have been found to be somewhat sensitive to moisture, and hence not closely reproducible unless the specimens are thoroughly dried and kept dry throughout the measurements, so it is possible that some of the specimens on which the measurements, the results of which are given in the Table, were carried out were insufficiently dry. The barium strontium zirconates and the strontium zirconate-titanates do not show any sensitivity to moisture.

The dielectric materials prepared as described in the above example, and listed in the Table, are suitable for use as resonators for filter elements, for example in the form of discs. Suitably shaped plates of the materials, of thickness about 1 mm, can also be used as substrates for integrated microwave circuits to be operated at frequencies of 1 to 5 GHz.

It will be appreciated that a device in accordance with the invention may incorporate more than one dielectric component as specified. For example, a microwave filter may comprise a number of dielectric resonators distributed along the axis of a waveguide used below its cut-off frequency.

Two specific microwave devices in accordance with the invention are shown in the accompanying drawings and will now be described by way of example. In the drawings in which like parts in the different figures are indicated by the same reference numerals

FIG. 1 shows, in sectional elevation, a bandpass filter incorporating five dielectric resonators;

FIG. 2 is a sectional plan view of the filter shown in FIG. 1;

FIG. 3 is a transverse section of the filter shown in FIGS. 1 and 2, drawn on the line III—III of FIG. 1;

FIG. 4 is a plan view of a microstripline circuit on a dielectric substrate; and

FIG. 5 is a section drawn on the line V—V of FIG. 4.

Referring to FIGS. 1, 2 and 3 of the drawings, the relationship between which is indicated by the lines I—I and II—II on FIG. 3 and III—III on FIG. 1, the device shown is a narrow band, high Q, filter designed to operate at a frequency of 4 GHz, comprising five resonator discs 1 formed of a dielectric material of a composition as specified in accordance with the invention, suitably one of the materials listed in the foregoing Table, each disc having a diameter of 20 mm, a thickness of 4 mm, and being adapted to resonate in the TE_{011} mode. The resonator discs are supported in a copper outer casing 2, suitably 14 cm long and 3.5 cm square in cross-section, by means of a tube 3, cylindrical spacers 4 and rings 5, all formed of a low loss, low permittivity dielectric material, for example the material sold under the Registered Trade Mark "Rexolite," the tube 3 being closed at both ends by copper caps 6. The resonator discs 1 have central holes 7 into which are inserted rods 8 of the same dielectric material as the discs themselves, and tuning screws 9 are inserted through the casing 2 to bear upon the rods 8 for adjusting the position of the rods in the holes 7, in order to adjust the resonant frequency of the discs as required.

As shown in FIGS. 2 and 3, two 50 ohm Type-N connectors 10 are attached to the casing 2, one at each end of the resonator disc assembly; copper coupling strips 11, 12, for signal input and output respectively, are soldered to the center pins 13 of the connectors, which pass through apertures in the casing 2, and the copper strips are supported within the filter cavity by rings 14 of the same dielectric material as the members 3, 4 and 5, referred to above.

FIGS. 4 and 5 of the drawings show a filter circuit in 50 ohm microstripline, 15, carried on a substrate 16 in the form of a rectangular plate of a dielectric material of a composition as specified in accordance with the invention. The substrate may be, for example, 15 mm long, 12.5 mm wide and 0.8 mm thick and, as shown in FIG. 5, has a continuous metal coating 17 on the face opposite to that on which the stripline circuit 15 is carried. Both the circuit 15 and the coating 17 suitably consist of a layer of chromium covered with a layer of gold: these layers are formed on both sides of the dielectric plate by evaporating first chromium and then gold on to the faces of the plate and finally increasing the gold layer to the desired thickness by electroplating; part of the coating is then removed from one face of the plate by photo-etching, to leave the desired circuit **15**.

We claim:

1. A microwave bandpass filter comprising in combination

a. input means,

b. output means, and

c. coupling means for coupling input microwave signal energy to the output means,

d. said coupling means comprising at least one resonator in the form of a body of dielectric material arranged to be subjected to the microwave so that the response of the bandpass filter depends on the permittivity of the dielectric,

e. the said resonator body being formed of a ceramic dielectric material consisting of at least one compound of the general formula ABO_3,

  i. wherein A is a metal of the group consisting of barium, strontium and calcium and

  ii. B is a metal of the group consisting of zirconium and titanium,

  iii. the composition of the material being so chosen

    A. that the atomic ratio of zirconium to titanium is in the range of 80:20 to 100:00,

    B. that if both barium and titanium are present the proportions thereof are such that barium titanate does not constitute more than 10 mole per cent of the material, and

    C. that the material will have, at frequencies in the range of 400 MHz to 30 GHz,

      I. permittivities in the range of 25 to 75,

      II. a temperature coefficient of permittivity which is substantially constant with changes of temperature, and

      III. a loss tangent not exceeding 0.005 at 20° C., and

f. wherein the said resonator body has a hole formed therein, and

g. there is provided a rod slidable in said hole and tuning means coupled to said rod to adjust the position of said rod in said hole whereby to vary the resonant frequenty of said body.

2. A microwave bandpass filter according to claim **1**, wherein the said rod slidable in the hole in the resonator body is composed of the same ceramic dielectric material as the resonator body itself.

3. A microwave bandpass filter according to claim **1**, which includes a housing of low permittivity dielectric material and wherein said body of said ceramic material is in the form of a disc, said disc being disposed within said housing, and said input means and said output means being disposed on said housing on opposite sides of said disc.

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