High K Dielectric Resonator Antenna

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Abstract: - The microwaves are used for both civilian and military applications for communication and detection. Due to the emerging applications and the need for more bandwidth as well as for high speed, there is a strong competition for ultra high frequencies devices. As it is know the size of different kind of microwave components is in a certain relation with the wavelength divided by root square of the dielectric permittivity. So the size of microwave component can be decreased by increasing the dielectric permittivity.

Dielectric materials based on TiO_2 are recommended for applications in electromagnetism and optics due to their nonlinear properties, to high value of the dielectric permittivity and their temperature behavior.

The paper describes very shortly the technology applied to manufacture high dielectric permittivity materials based on TiO_2 and a dielectric resonator antenna manufactured with these materials. The experimental data measured for dielectric antenna are presented.

Key words: high K dielectric materials, dielectric resonator, antennas

1. Introduction

Last technological developments in the field of wireless communication and radar systems led to one of the most spectacular development of dielectric materials technologies and microwave devices. When talking about high permittivity dielectric materials one should take into account the main requirements for microwave passive devices:

1. The miniaturization is one of the most important requirement which supposes to manufacture dielectric compositions with very high dielectric permittivity (ε_r) and is requested in order to decrease both the size and the weight of microwave devices.
2. The stability of the parameters with the temperature. Usually the temperature ranges from -40^0 to +100°C and the resonance frequency variation has to be less than 10ppm/°C. The variation of the resonance frequency with temperature depends on the temperature coefficient τ_ε by $\tau_f = -1/2\ \tau_\varepsilon - \alpha$, where α is the thermal expansion coefficient. So τ_f is dominated by τ_ε that changes from –2000 to +2000 ppm/°C on casual dielectric materials especially the ones with $\varepsilon_r > 30$. The result is that there are very few materials, which can be used in these applications.
3. The dielectric losses ($tg\delta$) should be very low, too, so the quality factor has to be higher than 1000.

2. Dielectric material (barium neodimium titanate -BNT) description

Ferroelectric ceramics with formula $BaO\text{-}Nd_2O_3\text{-}TiO_2$ (BNT) are very interesting for applications in microwave domain as they have $\varepsilon_r = 80 \div 90$ and $Q = 2000$ for frequencies up to 3 GH. High density values and adequate microwave parameters were obtained by adding 0.5 mol PbO substitution for BaO. The decrease of the Curie temperature with the increase of the Nd_2O_3 concentration was observed. For the sample with 28 wt % Nd, pyroelectric data indicate Curie temperature around 75 K, therefore, at room temperatures, the materials are in paraelectric phase.

Several high frequency and microwave applications require ferroelectric materials. The high dielectric constant, low losses and controlled temperature coefficient of resonant frequency are essential for dielectric resonators, planar antennas and substrates for hybrid integrated circuits [1]. However, due to the strong variation of the permittivity in the ferroelectric phase and around the Curie point T_C, the ferroelectric materials can be used only in the paraelectric phase.

The BNT dielectric materials, which are ternary compositions BaO-TiO_2-Nd_2O_3 [2,3], are very attractive for microwave devices due to their high dielectric constant and low losses in the microwave range. Most of the applications use the BNT material in paraelectric phase, far from the ferro-para transition. The Curie temperature is reduced with the increase of the Nd concentration.

3. Preparation of dielectric material

The BNT samples were prepared by solid state reaction technique. Reagent-grade oxides and salts (TiO_2, Nd_2O_3, Pb_3O_4, NiO, ZnO, $BaCO_3$) were used as raw materials. The raw materials were ball–milled for 2h in distilled water and then dried at 130 °C. Three type of dopants were added in order to obtain optimum high frequency characteristics: 0.3 ÷ 0.5 mol PbO, substitutional for BaO, and NiO and/or ZnO (< 0.2 wt %).

Ni and Zn ions were added in order to obtain higher densities at lower sintering temperatures. They act as grain-growth inhibitors with benefic effects on quality Q factor at high frequencies. The BNT compositions were synthesized at 1200 °C for 2h. After milling with organic binder, the powders were pressed into disks 18 mm in diameter and (1.2 ÷ 1.5) mm thick. Cylindrical dielectric resonators of 10 mm diameter and 5 mm height are also obtained. The samples were subsequently sintered in air at temperatures varying between 1210 °C and 1350 °C for 2 ÷ 3 h.

The obtained samples were cut, cleaned and then treated at 150 °C for 15 hours in order to eliminate residual water from the porous structure. The X-ray diffractometry (XRD) were utilized to investigate the structure of these ceramics.

4. DIELECTRIC PROPERTIES

Low frequency dielectric measurements were performed on the samples of 1 mm thick with a self-acting RLC bridge at 1 kHz. Some samples were measured in the range – 160 °C to + 100 °C.

Microwave characteristics were obtained by using the Hakki–Coleman method [4]. Samples of 9 mm diameter and 7.5 mm height were positioned in a Courtney test fixture. The microwave measurements were performed using a computer aided measurement system in the 1 ÷ 12 GHz frequency band with the HP 8757C network analyzer and HP 8350B sweep generator as the main system components.

Ceramic samples with Nd_2O_3 content in the range 2 ÷ 29 wt % were investigated in order to study the changes in the BNT structural and dielectric properties with the increase of the Nd_2O_3 content. A typical X-ray diffraction (XRD) pattern shown in Fig. 1 contains the diffraction lines of $BaNd_2Ti_5O_{14}$ with the specific orthorhombic structure as dominant phase and few peaks which can be attributed to $BaTi_4O_9$. The crystallite mean dimension (*D*) was in the range 2-5 μm.

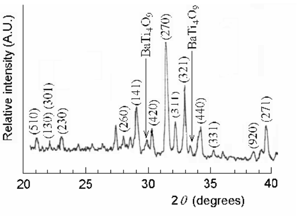

Fig. 1 X-ray diffraction pattern for BNT ceramic with 0.28 wt % Nd_2O_3 and 0.5 mol Pb ceramic sintered at 1250/2h

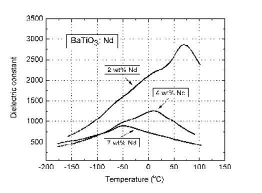

Fig.2 Dielectric constant versus temperature of BNT samples sintered at 1350 °C

In order to obtain samples in paraelectric state at room temperature, the temperature dependence of permittivity was analyzed at low frequencies (1KHz). The ferroelectric transition temperature and the dielectric constant decrease with the increasing Nd content. These results are presented in Figure 2. The Nd effect on BNT properties is to depress the ferroelectric–paraelectric transition to lower temperatures, depending on Nd concentration. For 7 wt % Nd_2O_3 (-50 °C) exhibit a slow decrease of the dielectric constant with the temperature increase, referring to a region far from the ferroelectric-paraelectric transition. As the dielectric measurements could not reach the peak value for some BNT samples such as the sample with 28 wt % Nd_2O_3 at low temperatures, pyroelectric measurements were used as an alternative method to find the transition temperature related at around 75 K.

Few dopants such as PbO, NiO, ZnO added for some samples in order to improve structural and microwave properties allowed the control of materials characteristics, as shown in Table 1. The Pb addition improves the dielectric properties in microwave range. Samples with 0.5 mol PbO show high dielectric constant ($\varepsilon_r = 85 \div 88$) and a temperature coefficient τ_f of the resonant frequency in the range from -30 ppm/ °C to -20 ppm/ °C.

Table 1. $(Ba_{1-x}Pb_x)Nd_2Ti_5O_{14}$ samples measured at f_{meas} frequency. f_{max} denotes the maximum frequency for a applications which require a maximum dielectric loss tangent of *tan δ.* All the samples were doped with 0.2 wt % NiO.

BNT Sample	Sintering temperature (°C)/ Sintering time	x (Pb content)	Zn wt %)	ε_r	*tan δ* (x 10^4)	f_{meas} (GHz)	f_{max} (GHz)
1	1260 / 3h	0	0	72	2.7	4.8	> 8
2	1260 / 3h	0	0	71.9	2.9	4.8	> 8
3	1260 / 3h	0	0	72.3	2.6	4.8	> 8
4	1250 / 2h	0	0	80.8	10	4.9	4.6
5	1260 / 2h	0	0	78.4	10	5	4.9
6	1250 / 2h	0.33	0	83.4	7.8	4.5	5.7
7	1260 / 2h	0.33	0	85.3	6.9	4.5	6.4
8	1230 / 2h	0.5	0	84.2	9.2	4.7	5.0
9	1240 / 2h	0.5	0	85.0	8.8	4.7	5.3
10	1250 / 2h	0.5	0	87.6	8.8	4.6	5.2
11	1260 / 2h	0.5	0	86.6	9.1	4.7	5.2
12	1210 / 4h	0.33	0.2	85.4	7.1	4.4	6.1
13	1240 / 2h	0.33	0.2	85.6	7.5	4.4	5.8
14	1250 / 2h	0.33	0.2	85.6	7	4.4	6.2
15	1260 / 2h	0.33	0.2	86.2	6.8	4.4	6.4

The maximum frequency of use of a BNT material can be calculated by observing that the $Q \cdot f$ product of a dielectric resonator is a constant on a large frequency range. For example, if a certain application requires a material with losses $tan\,\delta < 10^{-3}$, the values of the maximum frequency f_{max} are listed in Tab. 1. The addition of Pb and Zn increases the dielectric constant. Nevertheless, the undoped samples exhibit lower dielectric loss for lower dielectric constant than samples doped with Pb and Zn. The main applications of these materials are:

- dielectric resonators (DR);
- planar and dielectric resonator antennas.

5. Dielectric resonator antenna

The dielectric antenna is used for application where there is no much space available and there are special mechanical requirements. So it will be found on missiles, aircrafts, UAV etc. The antenna can be found as a dielectric stick when the permittivity is relatively low (it behaves as a dielectric waveguide, which radiates the electromagnetic energy) and as a dielectric resonator. The quality factor of a dielectric resonator may be as high as 20.000 for frequencies from 2 to 20 GHz. The operation principle of the dielectric resonator can be understood by studying the electromagnetic waves propagation through a dielectric waveguide. The structure of the electromagnetic field is presented on figure 3, 4 and 5. The first index shows the number of complete cycles of the field in horizontal plane and the second the number of radial cycles. When the firs index is 0 the electromagnetic field is circularly symmetrical. The electric field in cross section can be concentric circles (as E at TE_{01}), or radial lines (as H for the same mode). The pure electrical and magnetic fields do not exist for superior modes so both fields have stable longitudinal components. These modes are named electromagnetic hybrids (HEM).

When a section of the dielectric waveguide is used as a resonant cavity a standing wave regime is obtained. This device is called dielectric resonator. The most used mod is TE_{01d}, where the third index is used to show the number of half wavelengths in the axial direction of the waveguide. Here the third index, *d*, denotes that the length of the dielectric resonators is less then a quarter of a wavelength. The actual values depend on the value of the dielectric constant of the materials, on the substrate and on the separation between the two conductive planes. Usually the value of d it is not specified because it is not necessary.

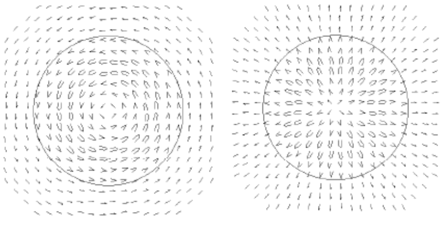

Fig. 3 TE_{01} in dielectric waveguide, left E field and right H field.

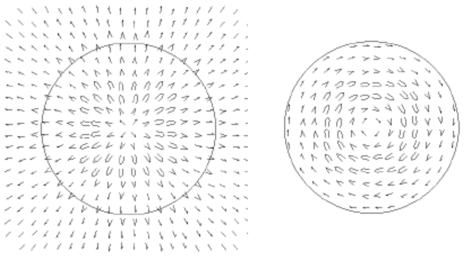

Fig. 4 TM_{01} in dielectric waveguide, left E field and right H field.

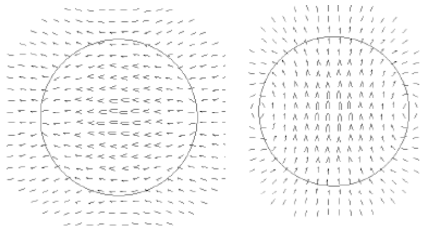

Fig. 5 HEM_{01} in dielectric waveguide, left E field and right H field.

When a dielectric resonator is not fully protected by a metallic surface, it may radiate and became an antenna. As can be seen on figure 6 the dielectric resonator is fixed on the metallic surface and the inner conductor of the feeding coaxial cable excites the antenna.

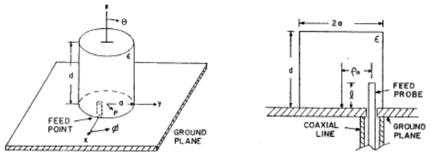

Fig. 6 Dielectric antenna fed with coaxial probe [5]

In [6] it had been demonstrated that the resonance frequencies are complex:

$$s_{m,n} = \sigma_{m,n} + j\omega_{m,n}\ , \qquad (1)$$

and that each solution corresponds to a resonant mode *m,n* which satisfies the continuity condition on the frontier. The ratio between real part and imaginary part is the quality factor:

$$Q_r = -\frac{\omega_{m,n}}{2\sigma_{m,n}} \qquad (2)$$

The minus sign shows that all passive circuits have their natural frequency on the left side of the complex plan, such as $\Gamma_{m,n}$ is a negative number, too. The natural frequencies as well as *Q* factors are presented in table no. 2.

Table 2.Resonance frequencies and Q factors for a dielectric resonator antenna ε_r=38, *a*=5,25mm and *h*=4,6mm [6]

Mode	f_r (GHz)	Q_r
TE_{01}	4.829	45.8
HEM_{11}	6.333	30.7
HEM_{12}	6.638	52.1
TM_{01}	7.524	76.8
HEM_{21}	7.752	327.1

The resonance frequency and the quality factor can be determined knowing the dimensions of the resonator and the value of the dielectric permittivity [9]. For instance the resonance frequency for HEM_{11} mode for a resonator having the radius a and the length h may be computed from formula:

$$k_0 a = \left(1,6+0,513x+1,392x^2-0,575x^3+0,088x^4\right)/\varepsilon_r^{0,42} \qquad (3)$$

where k_0 is free space propagation constant and *x=a/h*. Likewise he value of Q_r will be given by:

$$Q_r = x\cdot\varepsilon_r^{1,2}\left(0,01893+2,925e^{-2,08(1-0,08x)}\right)\cdot \qquad (4)$$

6. Experimental results

The dielectric resonators permittivity of the material was 86. In order to check the resonance frequency a vector network analyzer had been used. The S parameters can be seen on figure 7.

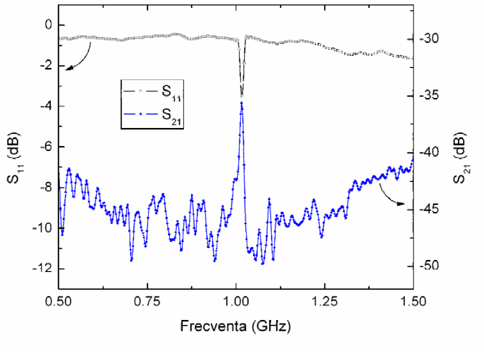

Fig. 7 S_{11} S_{21} for dielectric resonator.

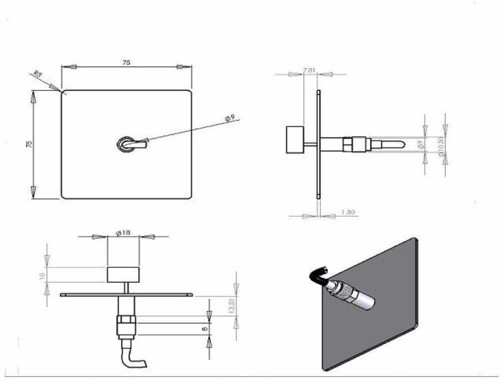

Fig. 8 Dielectric resonator antenna.

Based on simulations several types of dielectric antennas had been investigated. On figure 8 a sketch of the antenna is presented.
As can be seen on figure 8 there is a conductor between the feeding line and the dielectric resonator. It might be excited in either the center or eccentric. On figure 9, a dielectric resonator with the exciting point 3 mm off the center is presented.

Fig. 9. Dielectric resonator with the feeding point 3 mm off the center.

The pattern of the dielectric antenna with 3mm off the center feeding point is presented on figure 10.

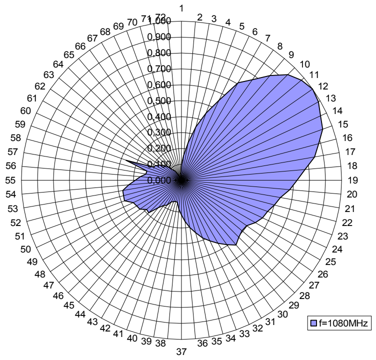

Fig. 10 Dielectric resonator antenna pattern

The input impedance of the antenna has been measured on the frequency range from 750 MHz to 1200MHz (fig.11).

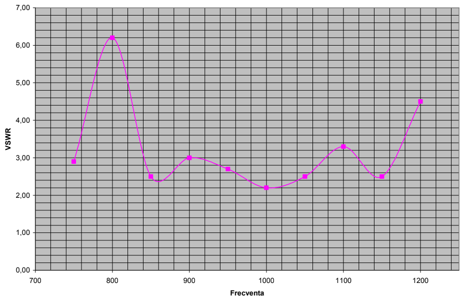

Fig. 11 Voltage standing wave ratio for a dielectric resonator antenna, from 750 MHz to 1200 MHz.

Another way to feed a dielectric antenna is on the center of the resonator, as in figure 11.

Fig. 11 Dielectric resonator with central feeding point.

The measured pattern of the antenna in this case is displayed on figure 12.

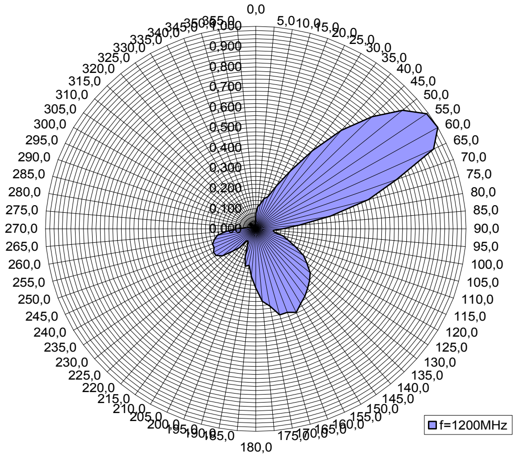

Fig. 12 Dielectric resonator antenna, central feed, for 1200 MHz.

Except one resonator antenna, measurements have been made using several resonators. For instance on next figures the results with five resonators fed 3 mm off the central point are presented.

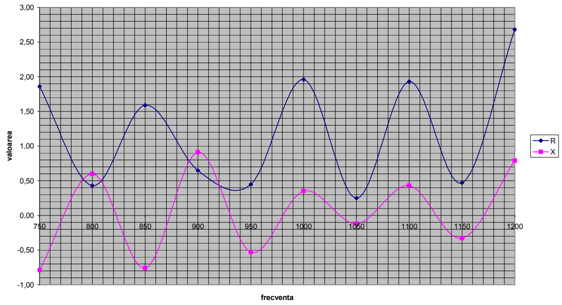

Fig. 13 The input impedance of a five resonators dielectric antenna, normalized at 50 Ω, in the bandwidth 750-1200 MH.

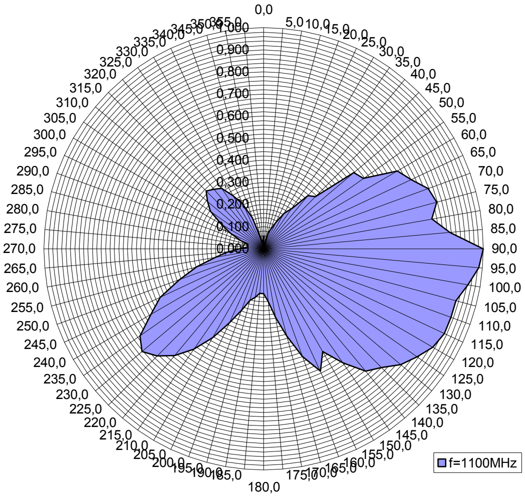

Fig. 14 Antenna pattern for five dielectric resonator antennas, for 1100 MHz.

7. Conclusions

1. High K materials used to manufacture different kind of passive microwave devices lead to component miniaturization. Because it is place at the interface between the electronic device and the propagation media antenna plays a critical role.

2. The miniaturization is strongly needed for wireless communication taking into account the spreading of WLAN systems.

3. The technology for high K materials is very complex but it allows manufacturing temperature stable materials with low losses.

4. In order to be used as an antenna a dielectric resonator has to be fed. The feeding may be made by coupling or using a probe. In the second case a hole has to be made into dielectric resonator which is a quite difficult job, talking into account the mechanical properties of the high K materials.

8. References

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