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Short Papers

Highly Stable Dielectric Resonator FET Oscillators

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Abstract —**The long-term frequency drift of GaAs FET oscillators with temperature has been analyzed theoretically and experimentally in view of stabilization using dielectric resonators. It was found that the dielectric material stability and quality factor should be within certain limits, and, in addition, that the resonance frequency over the temperature characteristic should be quite linear. Such a material has been developed on the basis of $BaTi_4O_9$ and $Ba_2Ti_9O_{20}$, and ultra-stable DRO's with frequency drifts of around ± 100 kHz for −50 to 100°C at 11 GHz (≈ ±0.06 ppm/K) have been realized.**

I. Introduction

Dielectric resonator stabilized oscillators (DRO's) are simple, small-sized, and consequently low-priced subassemblies the performances of which (concerning frequency stability, reliability, compactness, and electrical efficiency) have reached a level sufficient for several professional applications [1]. In work hitherto done on the stabilization of DRO's [2]–[4], it has, in fact, been recognized that the temperature properties of the active oscillator part, comprising the FET (or Gunn-diode) and the associated circuitry, are important for the stabilization mechanism, but an explicit investigation on this phenomenon has first been reported by the author in 1982 [5]. Similar to the work of Komatsu *et al.* [4], a stacked-type resonator with a temperature coefficient τ_f $(= df_r/f_r dT)$ constant over temperature has been reported in [5] and been used to realize highly stable DRO's. However, the stacked-type resonator does not represent an industrial solution. A new material performing the desired stability τ_f, linearity $(d\tau_f/dT \to 0)$, and quality factor Q_r, as defined in [5], in view of frequency stability, but also of the power degradation with temperature, had to be developed. This work has been done successfully at Philips Research Laboratories in Aachen, West Germany. This paper deals with the temperature behavior of FET DRO's using this new material, which allows even better results than achieved with the stacked-type resonator as reported before [4], [5].

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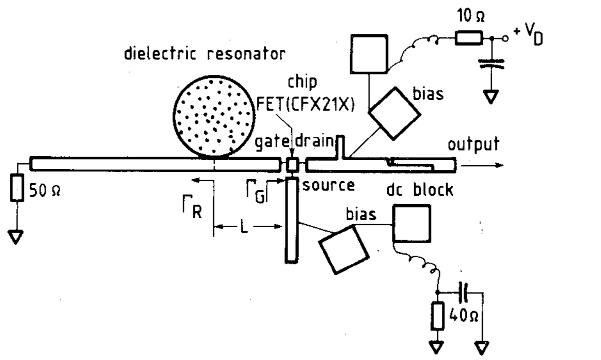

Fig. 1. Microstrip layout of GaAs FET DRO used in this work. Γ_R and Γ_G indicate the resonator and active circuit reflexion coefficients used in temperature modeling [5].

II. Modeling of Long-Term Frequency Stability

In this context, only the main results of the theoretical analysis presented in [5] on the temperature stabilization procedure of GaAs FET reflexion-type DRO's (Fig. 1) will be used. They can be summarized in the stabilization formula (1) and the temperature-stability-power-coupling chart of Fig. 3. This chart serves to demonstrate the stabilization limits for different resonator materials taking into account the oscillation power.

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TABLE I
DEPENDENCE OF QUALITY FACTOR (Q_0) OF THE USED DIELECTRIC MATERIALS ON TEMPERATURE, AS MEASURED IN A $TE_{01\delta}$ CAVITY AT 10.9 GHz

Dielectric material	Q_0 (Q_r)	$\Delta Q_0/Q_0$ (ppm/K)	τ_f (ppm/K)
Murata (Zr, Sn, TiO_4)	3100 (2730)	−2 300	9.6 (9.9)
Thomson (TiZr)	4040 (3470)	−10 500	9.9 (10.8)
Philips (Br 5) ($BaTi_4O_9/Ba_2Ti_9O_{20}$)	2900 (2650)	+830	4.0 (4.8)
Philips (Br 10) ($BaTi_4O_9$ $Ba_2Ti_9O_{20}$	2750 (2320)	+980	7.3 (8.0)
Stack ($BaTi_4O_9$&TiZr)	2920 (2540)	−730	5.9 (6.7)

In parenthesis are given average *in situ* quality factors Q_r, measured in a microstrip test fixture, and temperature coefficient values.

The fundamental relation between the oscillation frequency f, the temperature coefficient τ_f ($= df_r/frdT$) of the dielectric resonator, the coupling factor β between resonator and microstrip, the *in situ*[1] quality factor of the resonator Q_r, and the phase variation of the active circuit part $\partial\varphi/\partial T$ is [5]

$$\frac{df}{fdT} \approx \tau_f + \frac{\beta+2}{4Q_r}\cdot\frac{\partial\varphi}{\partial T}. \qquad (1)$$

This simple relationship is valid if $\partial[(\beta+2)/4Q_r]/\partial T$ is small compared to $\partial\varphi/\partial T$ (≈ -2500 ppm/K), as is the case for our dielectric materials on a barium–titanate basis. Resonators on a Ti, Zr, Sn basis show an important decrease of the quality factor with temperature as given in Table I and Fig. 2. In that case, (1) has to be used in its general form [5]

$$\frac{\beta+2}{4Q_r}\cdot\tan\left(\varphi - \frac{4\pi\cdot\sqrt{\epsilon_r}\cdot L}{C_0}\cdot f\right) = \frac{f-f_r}{f_r}. \qquad (2)$$

Fig. 2 shows the dependence of quality factors of some dielectric materials described in Table I as a function of temperature.

From (1), it can be concluded that frequency drift compensation occurs differentially at any temperature within the specified range. For a highly stable oscillator, therefore, the positive and negative differential parts of (1) have to keep balance at any temperature T

$$\tau_f + \frac{\beta+2}{4Q_r}\cdot\frac{\partial\varphi}{\partial T} = 0 \qquad (3)$$

where

$$\varphi(T) \approx \varphi_0 + \tau_\varphi\cdot(T-T_0) = \varphi_0 + \frac{\partial\varphi}{\partial T}\cdot(T-T_0) \qquad (4)$$

with $T_0 = -20°C$, $-20°C \leqslant T \leqslant 80°C$.

It has been found from direct measurements and via simulation using S parameters measured at different temperatures that the phase of the circuit part towards the FET decreases linearly with temperature [5]. The slope $\partial\varphi/\partial T$ of the active circuit phase is, therefore, constant over temperature and has values between −2500 and −2000 ppm/K.

Using (3) and (4), we obtain the optimum temperature coefficient of the dielectric material

$$\tau_f = -\left(\frac{\beta+2}{4Q_r}\cdot\tau_\varphi\right) \approx \text{const.} \qquad (5)$$

[1]*In situ* means that the resonator is posed on a 0.5-mm-thick quartz spacer and magnetically coupled with a 50-Ω microstrip on 0.635-mm-thick Al_2O_3 substrate in the same metallic box used for the DRO's.

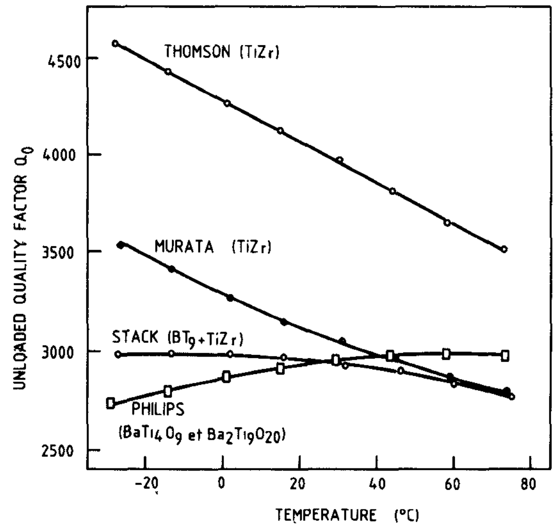


Fig. 2. Typical temperature dependence of quality factor of different dielectric resonator materials at 10.9 GHz.

TABLE II
THEORETICALLY ACCEPTABLE τ_f VALUES

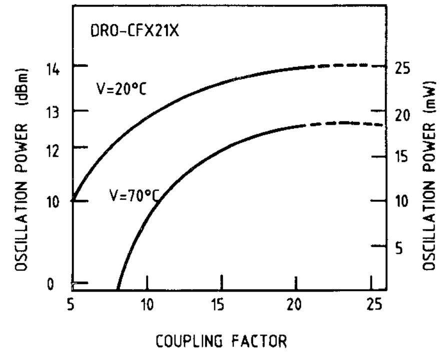
	without spacer		with spacer	
τ_f (ppm/K)	$Q_r = 1000$	$Q_r = 2000$	$Q_r = 3000$	
$\beta = 5$	4.4	2.2	1.5	τ_f min
$\beta = 25$	17	8.5	5.6	τ_f max

$\tau_\varphi = -2.5\ 10^{-3}$/K; spacer: 0.5-mm-thick quartz disc placed under the resonator.

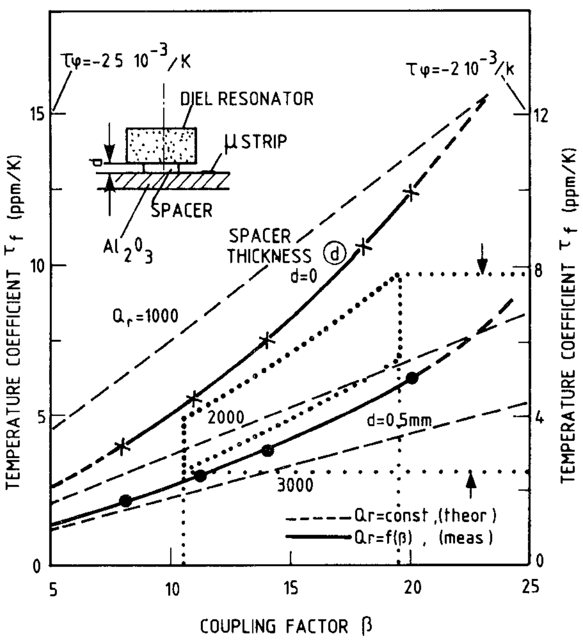
The coupling factor β can be adjusted within values of 5 to around 25. It seems, therefore, that any dielectric material with τ_f within large limits (1.5 ppm/K ⋯ 17 ppm/K) would be adequate for optimum oscillator stabilization as shown in Table II.

In practice, however, this rather large spectrum of acceptable τ_f values is restricted by oscillation power considerations and due to the observed dependence of Q_r on β ($Q_r = Q_r(\beta)$) in (5). The operation point follows the full τ_f curves rather than the dotted ones in Fig. 3(a) and (b) which visualizes these effects.

Fig. 3(a) illustrates the expected oscillation power at two different temperatures as a function of coupling of the resonator to the microstrip. Coupling factors of less than 10 seem not to guarantee operation at all temperatures. In addition, the power



(a)



(b)

Fig. 3. (a) Dependence of oscillation power on coupling factor between resonator and microstrip line (b) Influence of coupling factor β on optimum temperature coefficient of dielectric resonator material for two different mounting conditions of the resonator ($d = 0$ and 0 mm) and two possible slopes of the phase of the active circuit ($\tau_\varphi = 2.5\ 10^{+3}$ ppm/K and -2.10^{+3} ppm/K)

drop at higher temperatures increases for a lower coupling factor β. In conclusion, if the dielectric resonator is only weakly coupled, the power decreases rapidly with temperature and the oscillation may cease at higher temperatures.

Fig. 3(b) shows the temperature coefficients of dielectric resonator material that would permit an optimum frequency stabilization as a function of the coupling factor β. As mentioned before, the observed *in situ* quality factor Q_r of the resonators depends on the mounting conditions (existence and thickness of a quartz spacer) and also on the coupling factor β. Therefore, the effective operation point follows one of the solid (measured) lines rather than the dotted (ideal) ones. Taking now into account the results of Fig. 3(a), we can modify Table II to τ_f values that can be used practically for reasonable coupling factors β.

A further important quantity appearing in Table III is the "coupling sensitivity" of the resonator, defined simply as the variation of τ_f with $\beta(\partial\tau_f/\partial\beta)$. For high $\partial\tau_f/\partial\beta$ values, the stabilization of DRO's becomes extremely tedious and a small shift in coupling (geometrically spoken of less than 0.1 mm) can lead to stability jumps of plus or minus several ppm/K. Our

TABLE III
PRACTICALLY USABLE TEMPERATURE COEFFICIENT AND COUPLING SENSITIVITY OF SOME DIELECTRIC RESONATORS

ppm/K	without spacer		with spacer	
	τ_f	$\partial\tau_f/\partial\beta$	τ_f	$\partial\tau_f/\partial\beta$
$\beta = 10$	5	0.63	2.5	0.2
$\beta = 20$	12	1.0	6	0.5

experience shows that $\partial\tau_f/\partial\beta$ should not exceed roughly 0.5 ppm/K, if a reasonable stabilization procedure is expected. Referring to the results of Table III, this means, for instance, that the use of a spacer is strongly recommended even if its thickness should be less than 0.5 mm.

Nevertheless, these results show that dielectric resonator materials with *in situ* quality factors of the order of 1500 to 3000 and temperature coefficients between 3 and 7.5 ppm/K, *constant over temperature*, would be suitable to compensate for the frequency drift of DRO's using quartz spacers with a thickness between 0.1 and 0.5 mm. The usable $\tau_f - \beta$ area is given by the dotted frame in Fig. 3(b).

III. NEW DIELECTRIC RESONATOR MATERIALS

The typical inconvenience of available materials in view of developing ultra-stable DRO's is the temperature dependence of their temperature coefficient τ_f. We characterize "material linearity" using the average deviation from the linear law. Equation (6) defines this quantity

$$\delta_f = \frac{\sum_1^n |f_r(T) - (f_0 + \tau_f \cdot T)|}{\sum_1^n f_r(T)} \qquad (6)$$

where n is the number of temperature measurements, f_r the measured resonance frequency, and

$$f = f_0 + \tau_f \cdot T \qquad (7)$$

a straight line through the measured values with a slope τ_f defined by the minimum square deviation

$$\tau_f = \frac{n \cdot \sum_1^n f_r \cdot T - \sum_1^n f_r \cdot \sum_1^n T}{n \cdot \sum_1^n T^2 - \left(\sum_1^n T\right)^2}. \qquad (8)$$

Under these conditions, the materials of Table I are now shown (in Table IV) for the linearities δ_f.

As can be seen from Table IV, the stacked resonator has a better linearity than the other materials. As it has been pointed out in [5], the linearity of the stacked resonator is due to "mechanical compensation" of the nearly inverse characteristics of $Ba_2Ti_9O_{20}$ and TiZr dielectric materials used in this resonator.

Further investigations, however, done by D. Hennings at Philips Research Laboratory, Aachen, on the biphasic system $BaTi_4O_9-Ba_2Ti_9O_{20}$, showed that the minimum appearing in the $f_r(T)$ characteristics of $Ba_2Ti_9O_{20}$ ceramics near 0°C can be shifted to much lower temperatures, increasing thereby the linearity in the observed temperature region $T > -50$°C. Some of these materials are listed in Table IV (Br 4, Br 9, Br 10) and show indeed a higher linearity.

As reported by Hennings [6], the $BaTi_4O_9/Ba_2Ti_9O_{20}$ ceramics are not miscible but can be sintered to highly dense two phasic

TABLE IV
In Situ LINEARITY OF TESTED DIELECTRIC MATERIALS $f_0 = 10.9$ GHz, MEASURED WITH QUARTZ SPACER (0.5 mm)

Material	τ_f (ppm/K) (−20°C)	τ_f (ppm/K) (20°C)	τ_f (ppm/K) (75°C)	δ_f (ppm)
Murata (TiZr)	11.5	9.8	7.3	15 5
Thomson (TiZr)	13.5	9.3	6.3	32.5
Philips (Br 4)	4.7	5.7	6.7	9.4
Philips (Br 9)	8.0	8.1	7.9	2.9
Philips (Br 10)	8.1	8.0	7.9	2.1
Stack (B_2T_9&TiZr)	6.6	6.5	6.4	1.7
In comparison: pure $BaTi_4O_9$	−0.3	2.2	5.3	22.0

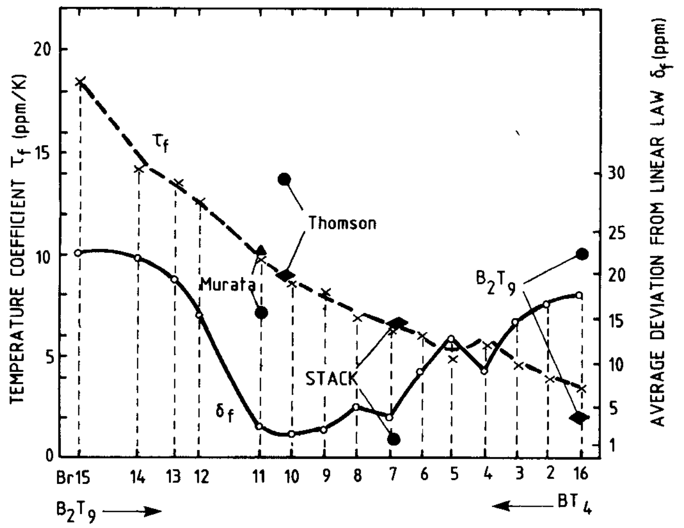


Fig. 4. Overview on temperature coefficient and linearity of the newly developed biphasic resonator materials on the basis of $Ba_2Ti_9O_{20}$ and $BaTi_4O_9$.

materials with dielectric constants of 38–40. The quality factors are of the order of 2500 to 2800 at 10.9 GHz and their temperature coefficient can be adjusted with composition from 2 to 18 ppm/K. Several probes of different compositions of the above materials have been tested on the temperature coefficient τ_f and on its variations with temperature. It was found that both τ_f and on $d\tau_f/dT$ are sensitively influenced by the composition of the new materials. We tried to summarize our measurements in Fig. 4, showing on the left axis the average temperature coefficient of the 10.9-GHz resonators and on the right axis the average deviations from the linear law expressed in ppm/K and ppm correspondingly.

In combining the results of Fig. 4 on stability τ_f and linearity δ_f of the different developed materials with those of Fig. 3(a) and (b), for an optimum τ_f, and β for the best stabilization of DRO's, we can easily conclude that the most appropriate material should be of lots Br 4–Br 7, where Br 4 would offer a better (lower) coupling sensitivity, but some nonlinearity (higher δ_f), whereas Br 7 would permit a better linearity but a more tedious stabilization procedure due to the higher coupling sensitivity $\partial\tau_f/\partial\beta$.

IV. RESULTS

Stable DRO's have been realized using a low-power GaAs FET (CFX 21X of RTC, gate length 1 μm, gate width 300 μm, $I_{DSS} \approx 70$ mA, $V_{p0} \approx -3.5$ V), and dielectric resonators made

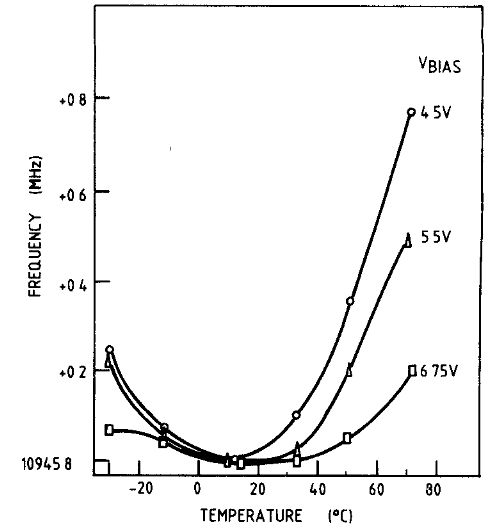


Fig. 5. Long-term frequency drift of GaAs FET DRO using a Br 5 dielectric resonator depending on bias voltage.

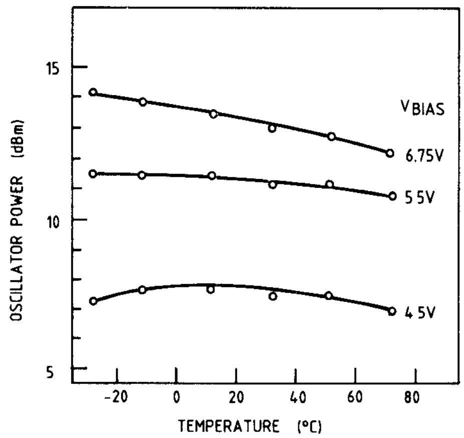


Fig. 6. Temperature dependence of oscillation power of the FET DRO using Br 5 resonator (84 mol% B_2T_9, 16 mol% BT_4) depending on bias voltage.

from the lots Br 4–Br 7. Although in all cases a good stabilization, resulting into a peak-to-peak frequency drift of less than 1 MHz ($\Delta f_{pp} < 1$ MHz), could be achieved, the coupling sensitivity for the higher τ_f materials made it difficult to fix (stick) the resonator and maintain the initially adjusted stability. So the best compromise was found to be the lots Br 5 and Br 7. Br 5 has a temperature coefficient τ_f of 4.5 ppm/K, an *in situ* quality factor Q_r of 2500, and an average deviation coefficient δ_f of 14 ppm. Figs. 5 and 6 show the power and frequency behavior of a DRO using this resonator material. Depending on the bias voltage, the overall frequency drift changes between 800 and 200 kHz for temperatures between −30°C and 75°C. The output power evidently increases with V_B but its variation with temperature also increases, probably partly due to excessive internal heating at higher dissipated power.

The frequency stability behavior is shown in Fig. 7. For $V_D \geq 6$ V, the slope of the $f(T)$ curve df/fdT is very small and fluctuates around 0. In this region, the peak-to-peak frequency deviation should be used, given on the right axis of the diagram.

A further example of a stable DRO using a resonator from lot Br 7 with higher τ_f (≈ 5.5 ppm/K) and better linearity δ_f (≈ 7 ppm) is shown in Fig. 8. The frequency drift is, on average, better compensated for (due to lower δ_f), but the peak-to-peak frequency

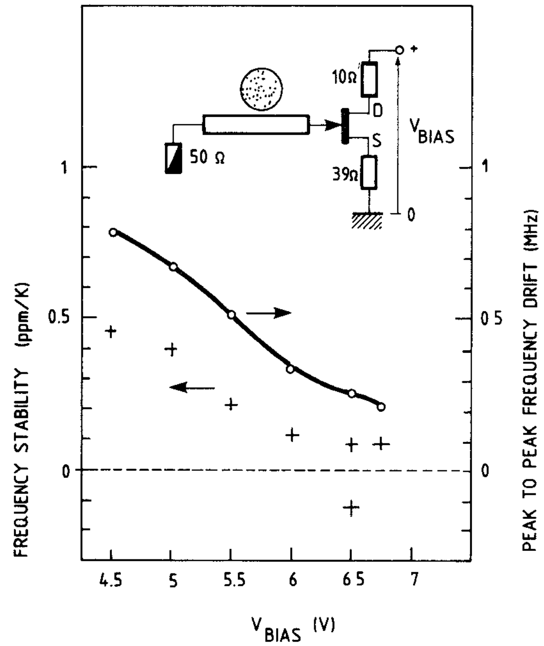


Fig. 7. Peak-to-peak frequency deviation and overall frequency slope of FET DRO using the Br 5 resonator for temperature variation between −30°C and 75°C.

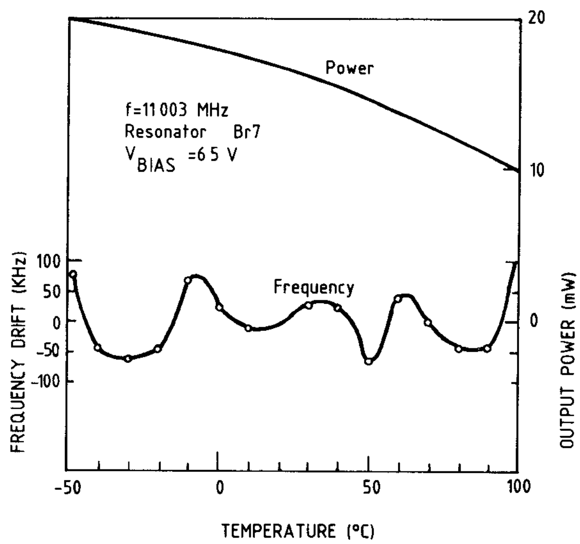


Fig. 8. Long-term frequency stability and power variation with temperature of FET DRO using the Br 7 dielectric resonator (76 mol% B_2T_9; 24 mol% BT_4).

deviation remains about ±100 kHz from −50°C to +100°C. In this case, the final positioning of the resonator was indeed more tedious than in the case of the Br 5 resonator.

Further experiments with several very stable oscillators using other dielectric materials have shown that the unavoidable long-term drift in the characteristics of the resonator and the FET in this free-running oscillator type cause at least a total frequency drift of 100 to 200 kHz over a 100 deg. temperature variation that can be considered as the natural fluctuation limit of this type of free-running oscillator.

On the other hand, the above-mentioned stabilities have been found quite reproducible when measured several times over a time period of several months.

V. Conclusion

We presented a general investigation of the stabilization procedure of GaAs FET oscillators using dielectric resonators. The influence of coupling, temperature coefficient, and quality factor of the resonators on frequency drift has been analyzed. New specifically developed homogenous materials on the basis of $Ba_2Ti_9O_{20}$ and $BaTi_4O_9$ have been tested and employed in order to realize ultra-stable DRO's. Reproducible stabilities of ±100 kHz over −50 to 100°C at 11 GHz have been achieved.

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The Annular Slot Antenna In a Lossy Biological Medium

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Abstract —**An integral equation is formulated for a coaxially fed annular aperture antenna. The integral equation in terms of the unknown tangential aperture electric field is solved numerically by the Method of Moments. The coaxial feed line is air filled while the exterior region consists of i) air, ii) fat or bone, and iii) muscle. Results are given for the aperture electric field, apparent input admittance, and contours of constant power absorption when the excitation frequency is 2.45 GHz.**

I. Introduction

The annular slot aperture antenna fed by a coaxial waveguide (Fig. 1) is a classic problem in electromagnetics [1]. Recently, the

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