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INVESTIGATIONS ON DIELECTRIC RESONATORS FOR APPLICATIONS BELOW 1 GHz

M. VALENTIN
(ENSMM Besançon, France)

R. E. ELCHEIKH
(LPMO: CNRS Besançon, France)

This paper is concerned with the design and analysis of UHF dielectric resonators operating below 1 GHz in certain applications where quartz-based acoustic resonators of modest performance or metallic cavities are customary employed. Lowest-order modes of circular and rectangular dielectric resonator are considered. Mode identification is obtained with a network analyzer and from visual observation of microwave energy detected by liquid crystal plates. Design and performance of filter, discriminator and oscillator using partly metallized $\lambda/4$ dielectric resonators are presented.

Introduction

Bulk Acoustic Wave Resonators (BAWR), Surface Acoustic Wave Resonators (SAWR), metallic cavities and Dielectric Resonators (DR) are used for filters, for the stabilization of fundamental frequency oscillators. In the 1 GHz frequency range, IF oscillators use crystal oscillators to achieve the necessary phase noise performance and the short term stability. The crystal oscillator frequency is increased to the required generator frequency by multiplication chains. In order to maintain the required long term stability the crystal oscillator has to be stabilized by means of an extremely stable low frequency reference signal (5 MHz). Multiplication increases the phase noise, requires filters with high out-of-band attenuation and provides spurious frequency lines. This method, in addition to being complex and costly, has a low efficiency and is possible only for low powers.

Because of these problems it would be better to utilise a highly stable source which is already in the IF frequency range.

Because of their size, metallic cavities are not very compatible with the structure of Microwave Integrated Circuits (MIC). Efforts have therefore long been made to replace these resonators by ceramic type and dielectric resonators have brought significant improvement in the design of microwave oscillators, filters and discriminators.

The existence of low-loss high dielectric resonators has been known for some time. A high dielectric material in free space exhibits radiation damping. If dielectric-constant is high ($\varepsilon_r \gg 1$) the relative damping is small enough to allow the dielectric to resonate. Compactness, light weight, temperature stability, relative low costs, integration are improvements brought by dielectric resonator in microwave components.

Dielectric resonators function as low as 1 GHz to as high as 35 GHz. At the low end, the dielectric resonator is relative large and is thus not conducive to compact designs; at the high end, losses and dimensions become difficult to control. For these reasons, most DR applications are in the range of 2 to 30 GHz.

In this paper circular and rectangular dielectric resonator are analyzed for applications in Microwave Integrated Circuits below 1 GHz. A dielectric waveguide is constructed from two parallel metallic strips and a dielectric slab of rectangular cross section between strips and contacting each of the strips. This line is capable of extremely brod-band and high power operation and is used for realizing compact dielectric resonator in 800/900 MHz frequency bands for land mobile satellite communication systems.

1. Natural resonant frequencies of dielectric resonators

1.1. Circular dielectric resonator

The study of electromagnetic waves in dielectric waveguide [1], [2], [3], [4] is very helpful in understanding the operation of dielectric resonators. The shape of a dielectric resonator is usually a short solid cylinder or a rectangular block.

The electromagnetic fields in dielectric resonator of high permittivity ($\varepsilon_r > 100$) satisfy well the open-circuit boundary condition (OCB) of a magnetic wall: at the OCB the normal component of electric field and the tangential component of magnetic field vanish. By duality principle, the TM field patterns with magnetic boundary conditions are the same as those for the TE modes with electric boundary conditions.

In the following experiments, used material (Zr, Sn) TiO_4 offers low temperature coefficient, a dielectric constant $\varepsilon_r = 37$. So, to obtain a better solution for circular dielectric resonator, the field is considered inside the rod and outside the rod. Unlike the components inside, the components outside are to be exponentially decaying in the radial direction. The eigenvalue equation for the dielectric rod waveguide of radius a is {2}:

$$\left[\frac{J'_m(x)}{x} + \frac{F(x)}{\varepsilon_r}\right]\left[\frac{J'_m(x)}{x} + F(x)\right] - \frac{\beta^2 a^2 m^2}{\varepsilon_r (k_0 a)^2} J_m(x)^2 \left[\frac{1}{x^2} + \frac{1}{y^2}\right]^2 = 0 \qquad (1)$$

where

$$F(x) = \frac{K'_m(y) J_m(x)}{y K_m(y)} \qquad (2)$$

$$y = \left[(k_0 a)^2(\varepsilon_r - 1) - x^2\right]^{1/2} \tag{3}$$

$$x = \left[k_0^2 \varepsilon_r - \beta^2\right]^{1/2} a \tag{4}$$

J_m is the Bessel function of the first kind and mth order, K_m the modified Bessel function of the second kind, $k_0 = 2\pi/\lambda_0$ the wave number of free space, β the waveguide propagation constant and x_{mn} the eigenvalues.

The eigenvalue diagram of Fig. 1 which is a tool for identifying the various modes of a dielectric resonator, gives the eigenvalues as functions of the normalized frequency $k_0 a$ for TE_{mn}, TM_{mn} and hybride HEM_{mn} modes in the dielectric rod for the experiment value of $\varepsilon_r = 37$. The HEM_{11} mode is the dominant mode of the rod and has no low-frequency cut off. For a rod of radius $a = 1.74$ cm the wavelength obtained from the diagram is $\lambda_g = 6.9$ cm at frequency 1 GHz and $\lambda_g = 2.9$ cm at frequency 2 GHz.

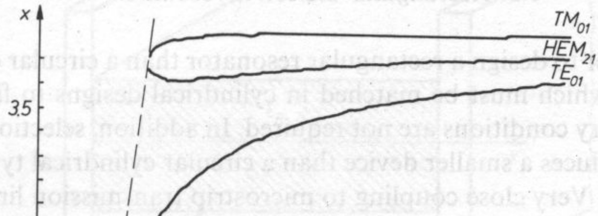

FIG. 1. Eigenvalue diagram of dielectric rod waveguide ($\varepsilon_r = 37$)

For a cylindrical rod of lenght l assuming that only flat surfaces satisfy the OCB condition, the value of x_{mnp} at resonance is:

$$x_{mnp} = \left[k_0^2 \varepsilon_r - \left(\frac{p\pi}{1}\right)^2\right]^{1/2} a \tag{5}$$

The lowest resonance frequency belong to the HEM_{111} resonance and the next higher is TE_{011} mode. The most consistent results were obtained with the TE_{011} mode for which no electric field component existe normal to the dielectric surface. Fig. 2 shows resonant modes for a dielectric resonator ($a = 1.74$ cm, $l = 1.54$ cm) coulped in reaction to microstrip line.

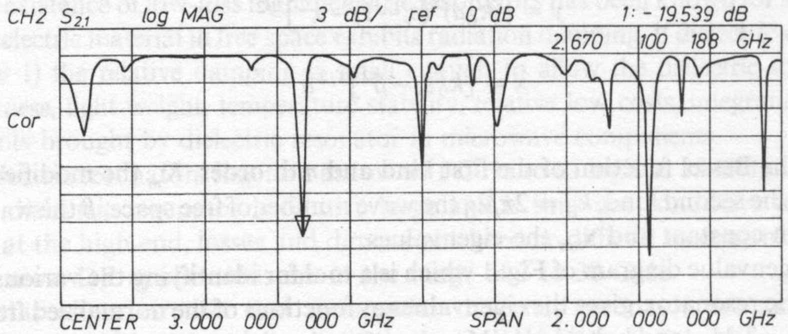

FIG. 2. Transmission coefficient of a circular dielectric resonator ($\varepsilon_r = 37$; $a = 1.74$ cm; $l = 1.54$ cm)

1.2. *Rectangular dielectric resonator*

It is much easier to design a rectangular resonator than a circular one: Bessel and Hankel functions, which must be matched in cylindrical designs to find a root that satisfies the boundary conditions are not required. In addition, selection of the proper resonant mode produces a smaller device than a circular cylindrical type designed for the same frequency. Very close coupling to microstrip transmission line can be easily obtained.

In the range of very high frequencies called UHF (pratically from 300 MHz to 3 GHz) the dielectric resonator will be less cumberson if it is constitued from a dielectric line with a rectangular section and two metallized opposed faces. The structure with two conducting strips (electric walls) and a dielectric slab of cross section $a \times b$ is shown on Fig. 3 in a microstrip structure with a mechanical tuning.

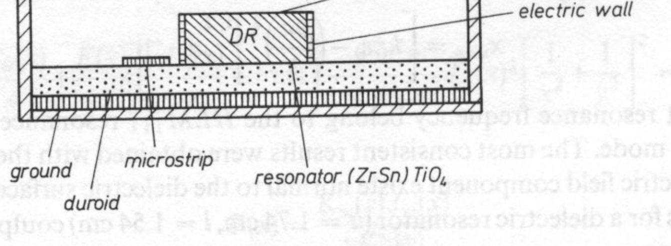

FIG. 3. Rectangular resonator in a microstrip structure

For high dielectric constant this line may be treated as a waveguide bounded by two magnetic walls and two electric walls. The fundamental mode is a quasi TEM mode. Small resonators ($b < \lambda_g/2$ where λ_g is the waveguide wavelength) are treated as line resonators and classified as quasi TEM resonator. A quarter wave resonator is obtained by metallizing an extremity of a $\lambda_g/4$ length line. With larger width b, resonances with a field dependence on the x as well as on the z coordinate can be excited. These resonances can be analyzed from the parallel plane waveguide partially filled with a dielectric (Fig. 4). TE and hybrid modes can propagate on this line. The lowest order TE_{10} mode, which is the dominant mode, has no cut off and is well suited for operation in UHF band.

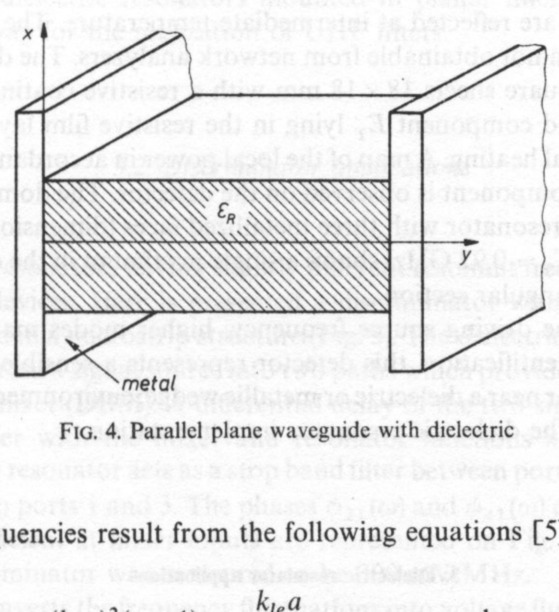

FIG. 4. Parallel plane waveguide with dielectric

Resonant frequencies result from the following equations [5]:

$$(k_0 a)^2(\varepsilon_r - 1) = \frac{k_{1e}a}{\cos k_{1e}a}, \quad \text{even modes} \tag{6}$$

$$(k_0 a)^2(\varepsilon_r - 1) = \frac{k_{10}a}{\sin k_{10}a}, \quad \text{odd modes} \tag{7}$$

where $k_1^2 = \omega^2 \mu_0 \varepsilon_1 - \beta^2$ is related to the propagation constant β, frequency ω and properties of the dielectric (μ and ε_1); $(k_{1e}a)$ must be between 0 and $\pi/2$, π and $3\pi/2$ ... and $(k_{10}a)$ must be between $\pi/2$ and π, $3\pi/2$ and 2π ... Single mode (TE_{10}) can exist if:

$$k_0 a < \frac{\pi}{2\sqrt{\varepsilon_r - 1}} \tag{8}$$

2. LIQUID crystal: an aid in the design and test of dielectric resonator

The evanescent nature of the field patterns requires that the resonator is screened by a metallic housing to avoid radiation losses and environmental influences. Providing the metallic walls are sufficiently distant from the resonator, conduction losses in housing are minimal. Much work has been undertaken in order to establish theories for resonant frequencies and in order to allow unambiguous identification of higher order mode pattern.

The technique of using liquid crystal detector plates for visual observation of microwave energy provide a quick and effective means to identify modes by looking the field map. The liquid crystal used in the present experiments is encapsulated with an active temperature range of 26–39°C. It reflects red light at 27°C and blue light at 33°C. Intermediate colors are reflected at intermediate temperature. The detector provides a type of information not obtainable from network analyzers. The devices used in this paper are several square sheets 18 × 18 mm with a resistive coating.

The electric field component E_T lying in the resistive film layer generates local currents causing local heating. A map of the local power in accordance with the square of the electric field component is observed on the detector. The dominant mode of the quarter wavelength resonator with three metallized faces (dimensions: 18 × 6 × 6 mm, resonant frequency $f_0 = 0{,}92$ GHz) shows a single maximum in the electric field in the non metallized rectangular section.

By adjusting the driving source frequency, higher modes may be observed. In addition to mode identification, this detector represents a sensible test for radiation losses, field behaviour near a dielectric or metallic wedge, environmental influences and aid the designer in the dielectric resonator implementation.

3. Dielectric resonator applications

All resonators are made of (Zr Sn) TiO_4 ($\varepsilon_r = 37$) with a O ppm/°C ± 0.5 ppm/°C temperature coefficient [6]. Passive devices (filters, discriminators) and active devices (oscillators) containing dielectric resonators are presented.

At frequencies higher than 2 GHz, only circular cylindrical resonators are considered. At about 900 MHz the physical dimensions of circular dielectric resonator are too large: only partly metallized dielectric resonator are used. Resonators are on a dielectric substrat (RT Duroid 6010) in the vicinity of 50 Ω microstrip lines. Resonant frequencies of rectangular resonator of dimensions 10 × 10 × 18 mm and 7 × 8 × 16.5 mm are 0. 88 GHz and 1.01 GHz respectively. Size reduction is obtained but metallic losses are increased. An unloaded Q, $Q_u = 600$, is measured with additional conductor losses at 0. 88 GHz.

3.1. Filter applications [7] [8]

Band pass filters are provided by a section of evanescent waveguide in which dielectrics resonators are inserted and directly coupled to each other. A band pass filter operating at X Band was constructed utillizing circular cylindrical resonators. The mode – chart (eigenvalue diagram) is a useful first step for filter design. The resonant frequency of each resonator, coupling coefficients between adjacent resonators and external Q'_s were adjusted so as to produce the desired filter response. Bandwidths up to 1.5% are obtained with two coupled dielectric resonators in a monomode tuning configuration. Insertion losses smaller than 0.5 dB are obtained. For greater bandwidths, several resonant mode are used.

Rectangular dielectric resonators mounted in planar microstrip line circuitry provide an easy way for the realization of UHF filters.

3.2. Discriminator applications

Usually two resonators having slightly different resonant frequencies are utilized in discriminator devices. Here is presented a discriminator with only one dielectric resonator mounted in a microstrip structure (Fig. 5). The dielectric resonator splits the signal emanating from a signal source into two paths which provide signal inputs to the double-balanced mixer (DBM). A differential delay of the two signal paths for phase quadratur, together with the mixer and resonator functions as a frequency discriminator [9]. The resonator acts as a stop band filter between ports 1 and 2 and as pass band filter between ports 1 and 3. The phases $\phi_{21}(\omega)$ and $\phi_{41}(\omega)$ of $S_{21}(\omega)$ and $S_{41}(\omega)$ transmission coefficient at mixer inputs are represented on Fig. 6. The slope of "*S*" curve of the discriminator was measured to be 300 mV/MHz.

The device converts the frequency fluctuations into voltage fluctuations which can be monitored and measured with an appropriate spectrum analyzer.

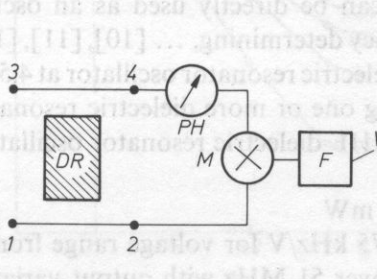

FIG. 5. Dielectric resonator discriminator

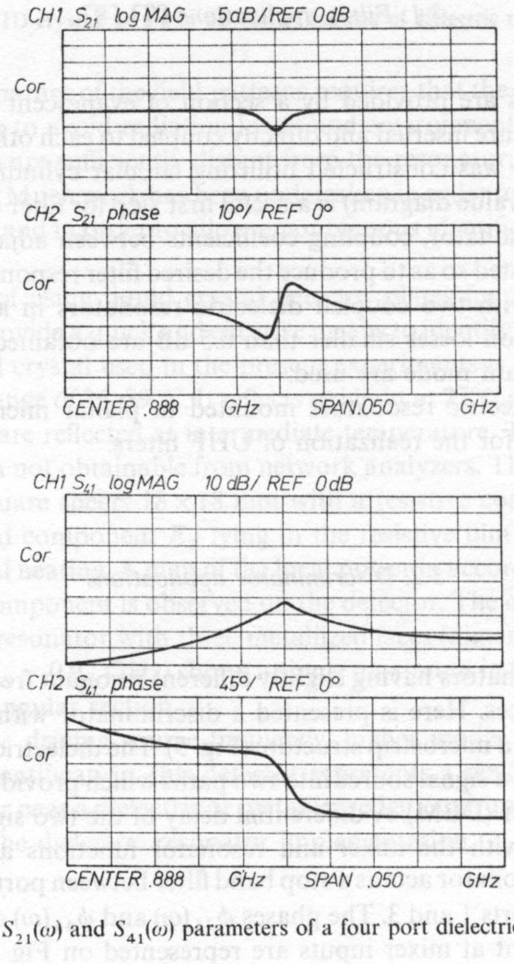

FIG. 6. $S_{21}(\omega)$ and $S_{41}(\omega)$ parameters of a four port dielectric resonator

3.3. *Oscillator applications*

Dielectric resonators can be directly used as an oscillator circuit element for feedback, matching, frequency determining, ... [10], [11], [12] [13]. PLOURDE [8] was the first to report a stable dielectric resonator oscillator at 4.5 GHz. New configurations have been developped using one or more dielectric resonators.

The performances of UHF dielectric resonator oscillator operating at 0.88 GHz are:

A output power of 50 mW
A pushing figure of–575 kHz/V for voltage range from 8 V to 11 V
A mechanical tuning over 51 MHz with output variation less 1 dB
An electrical tuning over 1.15 MHz with a varactor tuning
A frequency drift of – 4 ppm/°C for temperature range from 20°C to 50°C

A frequency stability expressed as Allan's variance $\sigma_y(\tau)$ of $3.5\,10^{-9}$ in the range 0.1 second to 10 seconds

A fractional frequency change < 3.6 ppm (observed during 12 days)

A frequency variation less than − 13 kHz over the temperature range from 10°C to 50°C.

The short term stability is presented on Fig. 7, for a dielectric resonator (18 × 6 × 6 mm) which presents a common point of oscillation frequency corresponding to a bias voltage $V_B = 10.6$ V (Fig. 8).

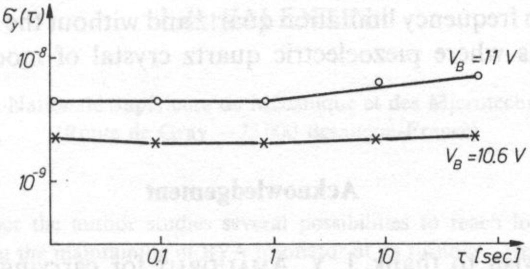

FIG. 7. Short term frequency stability: Allan's variance $< \delta_y(\tau) >$ versus the averaiging time

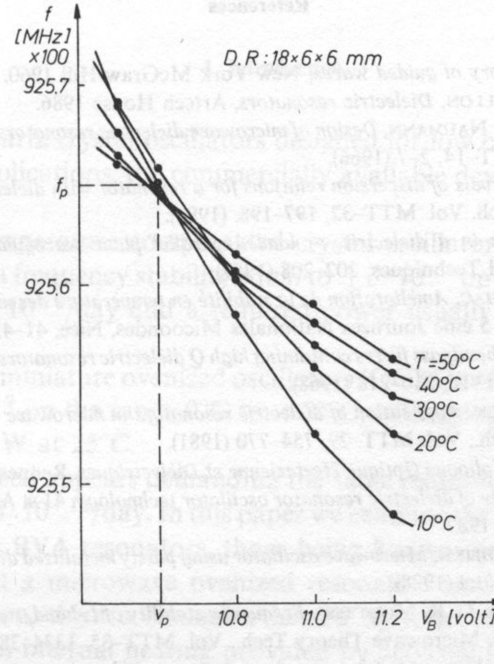

FIG. 8. Oscillation frequency as a function of the bias voltage V_B with the temperature T(°C) taken as parameter

For more frequency control, the same dielectric resonator can be used both as a feedback element and as dispersive element of a frequency discriminator. The DC output signal of the discriminator will be amplified and then applied to amplifier bias [14].

4. Conclusions

The dielectric resonators are readily applicable for compact, light weight, mobile systems used in the field of communication, surveillance and instrumentation. Results of experiments showed the feasibility of stable dielectric resonator at frequencies below 1 GHz without high frequency limitation quartz and without the supplying difficulty in certain applications where piezoelectric quartz crystal of modest performance are currently used.

Acknowledgement

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