Dielectric Resonator Oscillator Perturbed with Lossless Dielectrics

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Abstract

The perturbation of the dielectric resonator coupled to a microstrip line has been utilized to measure the perturber electrical parameters by means of the resonant frequency shift in the presence of the perturber. Two identical dielectric resonator oscillators operating at 4.25GHz are designed. One of the oscillator is perturbed with a sample. The shift in the oscillation frequency with respect to the reference oscillator is measured and used to determine the electrical properties of the sample.

1. Introduction

For the measurement of the electrical properties of the materials in the microwave frequencies, the cavity perturbation techniques have been widely used since 1950s [1]. The essence of these techniques is to introduce a small object into the resonant cavity and measure the shift in the resonant frequency of the selected mode which is directly related with electrical properties of the sample [2, 5]. However, in this type measurements, the sample geometry is restricted by the geometry of the resonant structure; therefore, the sample has to be in a certain size and shape. Dielectric Resonator (DR) perturbation methods can also be used for material measurements eliminating this drawback [3].

Dielectric resonators are ceramic materials which have high dielectric permittivity, high quality factor, and high temperature stability. They have much smaller size compared to cavity resonators, therefore, they are frequently employed in the design of frequency stable RF circuits, especially in oscillators. Previously, a semi–open boundary resonant structure realized by a DR placed between the conducting plates has been suggested for the permittivity measurements [3, 6]. However, integration of such type of measurement setup to on board devices is rather difficult and requires a measurement setup with external devices. To overcome this difficulty and design a portable material property measurement device, DR coupled microstrip lines could be used. DR coupled microstrip line structures are well studied and can easily be integrated with active devices. Perturbation of this type structure can be used for material measurements.

In this study, two identical oscillators based on DR coupled to microstrip lines, have been designed and realized for the measurement of permittivity of the lossless dielectric samples. One of the oscillators is perturbed with a sample. The shift in the oscillation frequency with respect to the reference oscillator is measured and used to determine the electrical properties of the sample. It has been successfully demonstrated that the shifts in the perturbed oscillator's frequency due to the presence of the sample can be measured.

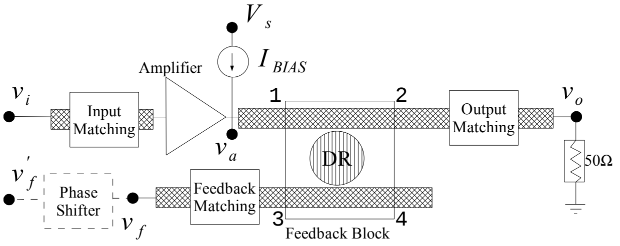

Fig. 1: The Dielectric Resonator Loaded Amplifier

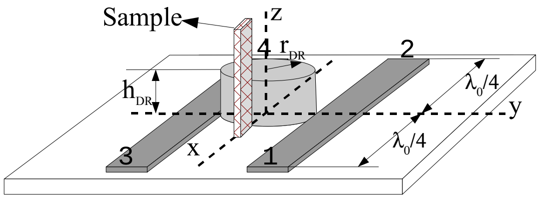

Fig. 2: The Dielectric Resonator coupled to microstrip lines

The proposed structure is especially useful for measurement of the electrical properties of the liquid or grained substances, although it can be used for sheets by employing suitable mechanical setup. The main advantage is that the sample shape is not restricted, as the setup can be calibrated for any sample geometry. The bare sample in Fig.2 is replaced by a thin glass tube which contains the liquid or the grained sample, when necessary, and the frequency shift is measured with respect to the frequency of the setup with the empty container. However the measurement range is limited by the half of the dielectric constant of the oscillator's DR.

2. Perturbed Dielectric Resonator Oscillators

2.1. Design of the DROs

The basic circuit diagram of a DR loaded amplifier circuit is shown in Fig. 1. Assume that S-parameters of the amplifier is known and the four port feedback block consists of the DR coupled to microstrip line which is shown in Fig. 2. The resonant frequencies of this structure depends on the dimensions of the DR, i.e. r_{DR} and h_{DR} and the dielectric permittivity of DR which is characteristically high. The quality factor Q of the circuit depends on the unloaded Q of the dielectric resonator which of order of several thousands.

The dominant quasi-$TE_{01\delta}$ modes can easily be excited by adjusting the distance between the resonator and the microstrip lines. The excitation ports on microstrip feed lines are placed at

$\lambda_0/4$ distance, where λ. is the wavelength of the dominant mode. Port 3 represents the feedback port. Note that, obtaining the S-parameters of the structure analytically is not possible. Hence, one starts with a 3D finite element simulation of DR coupled to microstrip lines in order solve port parameters.

Let :

$$G_{af}=\frac{v_f}{v_a},\quad H_{ia}=\frac{v_a}{v_i} \tag{1}$$

be the feedback and amplifier gains, respectively. The loop gain should satisfy the well known Barkhausen criteria i.e. $H_{ia}(\omega_o)\cdot G_{af}(\omega_o)=1$ for a stable oscillation. The feedback is only possible for the excited modes of the DR coupled to microstrips, hence, ω_o represents the related resonant frequency. The amount of the feedback depends on the coupling of DR to microstrip lines [4].

The input, output and feedback matching circuits and the coupling between the dielectric resonator and microstrips can be designed in order to satisfy the Barkhausen criteria and allow maximum possible output power at the chosen mode. The output power is limited by the available gain from the base amplifier and the amount of positive feedback required. In practice, the feedback loop gain is arranged to be larger than 1, in order to the oscillator have self-starting of sustained oscillation.

The input, output and feedback matching circuits are simple open single stub microstrip matching networks, whose lengths and stub positions are chosen for 50Ω matching. The input, output and the feedback ports have simultaneously matched.

In order to design matching circuits, first port 3 is terminated with 50Ω and the input and output matching networks are optimized in order to minimize input and output reflections, i.e. Γ_i and Γ_o form matched loads where the stub lengths and positions has been chosen be the optimization parameters. Then, the output port is terminated and the procedure is repeated for the input and the feedback ports in order to minimize Γ_i and Γ_f, simultaneously. Since, input matching is already determined for input—output matching, its parameters are chosen to be the initial values for input—feedback matching optimization. Since addition of the feedback match deteriorates input—output matching, one can restart the procedure by terminating the feedback matching network, and re-optimizing input—output and input—feedback matching networks. Then deteriorated input—output match is corrected similarly. After several steps of optimization which are initialized with parameters of previous step and appropriate port is terminated, the procedure converges to the optimal matching parameters.

In order to to obtain, self sustained stable oscillations the condition, $\sphericalangle v_i(\omega_o t)=\sphericalangle v_f(\omega_o t)$ must hold. However, the above procedure does not guaranty that the feedback signal is at correct phase,i.e, $\sphericalangle H_{ia}(\omega)\cdot G_{ia}(\omega)=0$. Defining:

$$\omega'_o=\underset{\omega}{argmax}\frac{|v_f(\omega)|}{|v_i(\omega)|} \tag{2}$$

which can be slightly different from the DR resonant frequency ω_0 because of the loading effects. Let:

$$\phi_o=\sphericalangle\frac{v_f(\omega'_o)}{v_i(\omega'_o)} \tag{3}$$

Then a phase shift 2π-ϕ_0 is required such that $\sphericalangle v_i(\omega'_o t)=\sphericalangle v'_f(\omega'_o t)$. With a low loss substrate, the phase shifter is simply a microstrip line with electrical length 2π-ϕ_0 at ω_0.

At this point as the feedback loop can now be closed, the DR oscillator is formed. The oscillation frequency is determined by the excited mode of the DR. Since the matching networks are optimized for the frequency of the dominant mode of DR, it is not possible that higher order modes are excited and frequency hopping may occur. Note that, in principle, no lumped passive elements are required except biasing elements and the phase noise performance is exceptionally good due to the high Q of the resonator.

The oscillation frequency also depends on the temperature, because both the amplifier response and the DR parameters depends on it. In order to avoid any frequency shift due to the shift in the temperature, temperature compensated MMIC amplifiers and dielectric resonators can be used.

2.2. Perturbation of the DRO

If a lossless dielectric sample is placed near the DR, the oscillation frequency shifts. It has been shown that the shift depends on the dimensions and the electrical properties of the sample, however, obtaining the relation between the frequency shift, the dimensions and the electrical properties of the sample is not possible analytically. Nevertheless, by keeping the dimensions constant, the frequency shift can be measured and compared to get accurate measurements of the electrical properties of the sample at microwave frequencies. The calibration can be done by standard dielectric materials and the measured frequency shift can be converted to actual measurement.

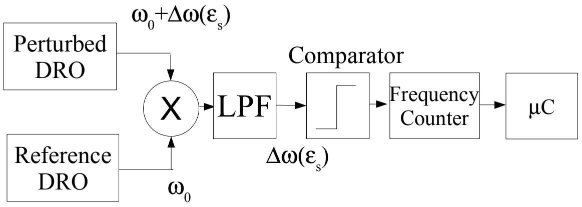

Fig. 3: The Measurement setup

Since the oscillation frequency also depends on the temperature, one can devise two identical oscillators kept at the same temperature. Instead of directly measuring the frequency shift due to the presence of the sample of permittivity ε_s, the frequency output of the mixer in Fig. 3 is measured, which does not depend on the the temperature shift. The setup is calibrated such that the output is zero in absence of the sample. The calibration is done by adding a simple metallic tuner above the reference oscillator or by means of adjusting the bias current slightly.

Care should be given for inter—modulation of oscillators, due to presence of the mixer. Otherwise, the oscillators can be synchronized disabling the measurement. This can be avoided by isolating oscillator outputs.

The accuracy of the measurement depends on the stability of the biasing of the oscillators and matching of the oscillators in absence of the sample. The setup could be improved by electronically fine tuning the reference before each measurement and controlling the temperature by a closed loop system.

The main advantage over classical material property measurement setups as cavity resonator or terminated transmission line methods is that it can be integrated to a self

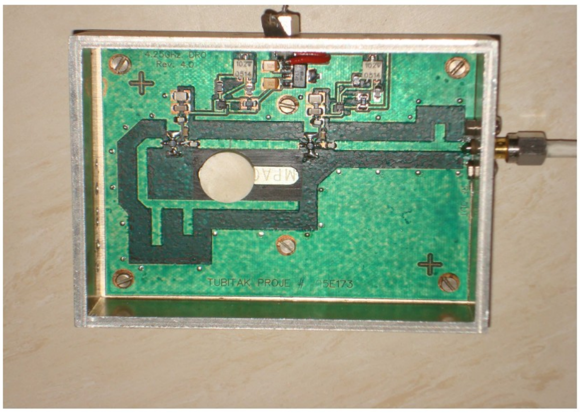

Fig. 4: Designed DR oscillators operating at 4.25GHz.

contained structure, which would require much less space. It is especially suitable for liquid measurements, since the structure can be perturbed by a test tube containing liquids or grained substances.

The range of the measurement is limited above by the relative permittivity of the dielectric resonator. The frequency shift saturates as the relative permittivity of the sample get closer to the DR's. Our FEM simulations indicate that the useful range is $1 \le \varepsilon_s \le \frac{\varepsilon_{DR}}{2}$. Above this range, the shift is almost in sensitive to ε_s .

3. Experimental Results

In order to demonstrate the proposed setup, we designed two identical DRO's using the procedure described above as shown in Fig.4. The base amplifiers are chosen to be HP MSA0886 cascadable Silicon Bipolar MMICs. The DRs are of type D8517 manufactured by Trans-Tech, with $2r_{DR}$=0.545" and h_{DR}=0.245" for which the dominant mode resonant frequency is approximately 4.25GHz. GaAS HMC213M double-balanced mixer and ADCMP604 rail-to-rail LVDS high frequency comparator ICs are used for the mixing stage. All circuits are designed on a Rogers Duroid 5880™ substrate.

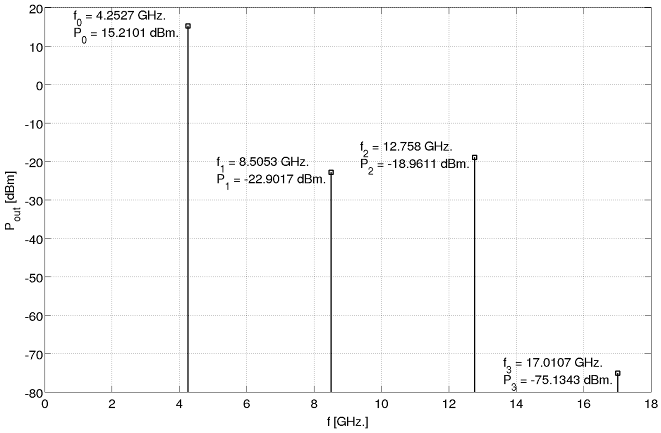

Fig. 5: The Output Spectrum of the designed DRO

The S-parameters of the DR coupled microstrip 4-port have been obtained using ANSOFT HFSS FEM simulation software. The optimization of the matching structures are then carried out using ANSOFT Designer/Nexxim software. Resulting oscillators are depicted in Fig. 4. The outputs of oscillators are isolated using isolation amplifiers of same type which are optimized as above.

The simulation results for the output spectrum of the designed oscillators are shown in Fig. 5. The harmonics are due to the nonlinearity of the amplifier, which can be minimized by carefully adjusting the feedback gain, but do not pose a problem since the frequency counter is insensitive to the harmonic content due to the hard limiter and only rising edges are counted. The actual measurement results are in complete agreement with the simulation results (Fig. 6).

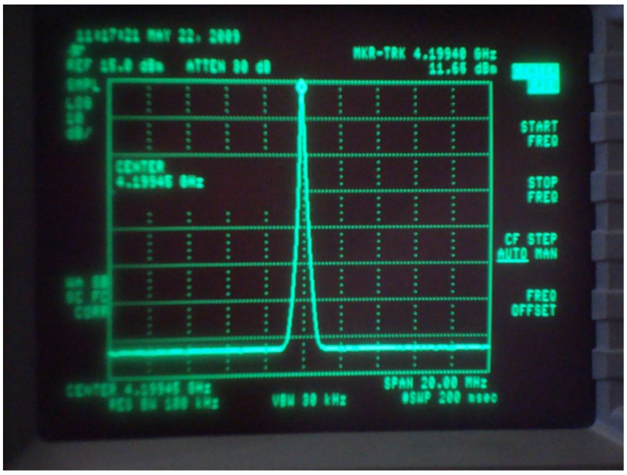

Fig. 6: Measured output spectrum for the DR oscillator.

The simulation result for the phase noise has been shown in Fig. 7. At this point no special emphasis is given to reduce the phase noise, which definitely effects the accuracy of the measurements. Nevertheless, due to the high Q of the DR, the oscillators have acceptable phase noise performance. Clearly, this can be improved by using specifically designed low noise band limited amplifiers.

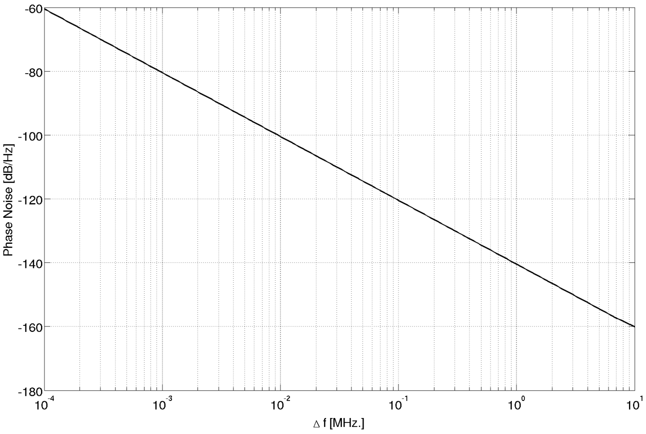

Fig. 7: The Phase Noise

Table 1 enlists some preliminary measurement results. The shift in frequency could be measured for several well—known substrate materials, however the accuracy of the measurements which depends on the factors like the temperature, the exact position and the thickness of the sample, has yet to be evaluated.

Table 1. Measurement Results

Material	Relative Dielectric Permittivity ε_s	Frequency Shift KHz.
Duroid 5880 h=0.78mm	2.2	~850
Taconic RF-35 h=0.50mm	3.5	~1300

It should be noted that the thermal equilibrium has to be reached in order to get accurate results. This indicates that close loop control of temperature is necessary. Currently, we are integrating PWM based temperature control to the oscillators which will also allow us to measure the permittivity at different temperatures.

4. Conclusions

In this study, a portable measurement setup for permittivity measurements of lossless dielectric materials has been proposed. The measurement setup consists of two identical dielectric resonator oscillators. The dielectric resonator of one of the oscillators is perturbed with the sample whose electromagnetic properties are to be measured. The design of these oscillators has been carried out using ANSOFT HFSS/Designer/Nexxim electronic design automation software. Design procedure for the oscillators has been explained and simulation results are presented. The outputs of the reference and the perturbed oscillators that are kept at the same temperature are then mixed and hard—limited to obtain the frequency shift due to the presence of the sample.

The over all system has the advantage over previous measurement setups that it can be integrated to a portable device and can easily be used for measuring the electrical properties of the liquids and grained substances.

The main drawback of the setup is that the permittivity can be measured at only single frequency. However, this can be overcame by using several DR's, or carefully exciting DR at different modes instead of the the dominant mode. Nevertheless, the setup is still very useful for the designs that aim specific frequency band and the permittivity of the design materials has to be known accurately beforehand.

5. Acknowledgments

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