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Radio proximity Doppler sensor with high K dielectric materials

I. NICOLAESCU*, A. RADU, A. IOACHIM[a], C. VIZITIU
Department of Communications and Military Electronic Systems , Military Technical Academy,
81-83 George Cosbuc Avenue, Bucharest,
[a]National Institute for Materials Physics, Bucharest, Romania,

One of the most important trend in electronic devices manufacturing is miniaturisation. Among other techniques used to decrease the physical dimensions of microwave devices one is to employ materials with high permitivity [1], providing that the dimension of the device is proportional to the wavelength in the material, which is square effective permittivity times less than the wavelengths in free space. The paper shortly presents the manufacturing process to obtain a high permittivity ZST ($(Zr_{0.8}, Sn_{0.2})TiO_4$) material used to build a dielectric resonator oscillator, which is used as a proximity Doppler sensor. Computed and experimental results as well as the procedure to measure the parameters of the Doppler sensor are presented. The sensor described in the paper may be considered as a short range radar device.

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Keywords: High K dielectric materials, Dielectric resonators, Radio proximity sensor

1. Introduction

The electromagnetic waves have more and more applications from wireless communications systems, which provide mobility to the user, to target detection, fire control systems, remote sensing, medical applications, through the wall detection systems, ground penetrating radar, security systems, speed measurements and, the last but non the least, proximity sensors. Anti-collision and proximity fuse systems are among the most important applications for radio proximity sensors. In the first case the mobile has to have several sensors despatch in different parts of the vehicle. They have to signal any object which closes at a certain distance from any part of the vehicle. To this end, the sensor has to continuously measure the distance between its position and any surrounding object. The second example refers to a military application which consists of measuring the distance between a projectile and its target in order to optimize the triggering moment of the explosion. As it is known a classical radar works in Fraunhofer region for which the plane wave condition is fulfilled and there is now coupling signal between the radar system and different objects located in that area. Unlike classical radar the proximity sensor has to work in very close range so the radar equation does not apply, providing that the electrical field does not decay inverse proportional with the distance between the radar and the target but with the square distance. Moreover, a strong mutual coupling between the sensor and the object will degrade the performances of the system.

2. Principle of operation

Radio proximity Doppler sensor may have 2 different channels for transmission and reception or one single channel used for both of them. The single channel solution is employed when there is a high reflected signal and little space available. The radio proximity Doppler sensor has to measure the range and, sometimes, the movement parameters for objects located at a short distances. The range measurement is carried on using the same principle as employed by any radar system but with specific requirements. Giving that the sensor is working at close range the separation between the sensor and the object is comparable with its dimensions. Also, for a small ratio of R/λ the direct and reflected wave fronts can not be considered spherical and, as a result, the structure of the reflected signal as well as its energetic and temporal parameters is different in comparison with the reflected signal for classical radar. The radio proximity Doppler sensors based on autodyne circuit have different principle of operation than the ones based on heterodyne receiver. The autodyne is recommended when space and weight restrictions are very tight, the reflected signal is quite high and the separation and the receiver sensitivity are low. In this case a common channel is used for both transmission and reception. As the oscillations are generated, a voltage E_A is created in the autodyne's antenna. The electromagnetic wave propagates towards the object and is backscattered to the antenna producing an induced voltage e_S (Fig. 1)

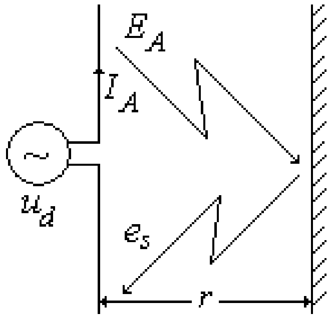


Fig. 1 The principle of operation of the autodyne.

The phase shift between E_A and e_S depends on the distance r and changes with 2π when r varies with $\Delta r = \lambda/2$. This oscillation of phase will produce a variation of the current in the antenna I_A, which will change voltages and currents within the autodyne circuit. These variations are the effect of interaction between the sensor and the object. The useful signal $u_d(t)$, at the output of the autodyne, has Doppler frequency.

3. ZST material

ZST materials were prepared by standard solid-state reaction technique. The X-ray diffraction pattern, presented in Fig. 2, showed that the compound $(Zr_{0.8}, Sn_{0.2})TiO_4$ was the majority phase, corresponding to the standard crystalline data.

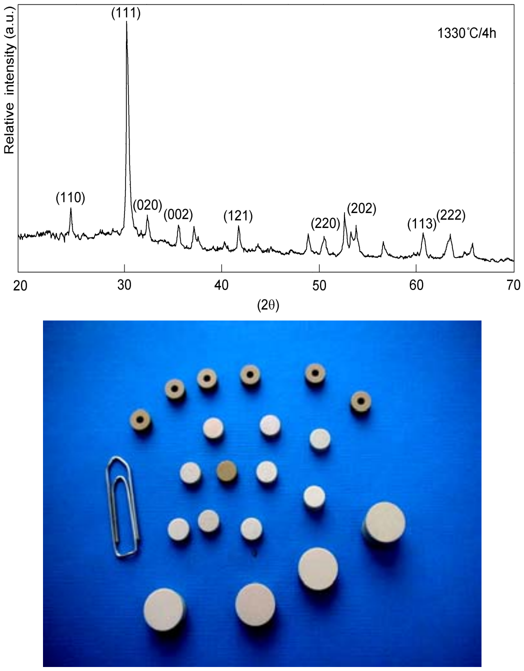


Fig. 2 X-ray diffraction pattern of ZST ceramic material. ZST cylindrical samples.

The ZST material was pressed and sintered into cylindrical samples of different dimensions, as shown in Fig. 2. The cylindrical samples were placed into a Courtney and the dielectric parameters were measured in the microwave range by using the Hakki-Coleman method. The measurements revealed values of the dielectric constant between 36.1 and 36.8, as shown in Table 1. A product $Q\text{x}f$, between the quality factor Q and the measurement frequency f, of more than 50,000 was achieved for samples doped with 0.2 wt % NiO. Furthermore, the measured resonance frequency temperature coefficient τ_f takes values between –4 and +4ppm/°C [2].

Table 1. Dielectric parameters, in microwave range, for ZST samples.

NiO (% wt)	Sintering time t_p (h)	Dielectric constant ε_r	tan δ ($\text{x}10^4$)	Product $Q \cdot f$ (GHz)
0	2.0	36.8	2.14	31,080
0	2.25	36.6	2.91	22,760
0	2.50	36.2	2.62	25,530
0.2	2.0	36.3	1.45	46,480
0.2	2.25	36.8	1.32	50,830
0.2	2.50	36.1	2.12	32,160

4. Dielectric resonator oscillator used for doppler sensor

4.1 Introduction

A typical oscillator essentially consists of an active device and a passive frequency-determining resonant element such as a dielectric resonator (DR), for fixed-frequency oscillators, or a varactor, for a tuneable oscillator. The emphasis has been on high output-power, low noise, small size, low cost, high reliability and high temperature stability. There are two categories of fixed oscillators: serial feedback and parallel feedback. In the serial feedback case the transistor gain must be higher, because the coupling from the resonator to the microstrip-line is not that strong. The coupling coefficient can be easily optimized by choosing the appropriate distance between the resonator and the microstrip line. The position of the DR along the microstrip line can be tuned for optimal performance. Therefore, the serial feedback configuration is a good choice [3]. Practically, a GaAs FET or a Si-bipolar transistor may be chosen as the active device for the oscillator. The Si-bipolar transistor is generally selected for lower phase noise characteristics, while the GaAs FET is required for higher frequencies. In practice, it is difficult to build a useful oscillator at frequencies above $f_{max}/2$, where f_{max} is the frequency where unilateral gain of the transistor equals unity. The oscillator had been designed using S parameters. The method provides no information about the output power, harmonics, phase noise or other parameters of possible interest. In general, the output power of the oscillator will approach the -1dB compression power (P_{-1dB}) of the transistor used as an amplifier if the DC bias is designed for maximum P_{-1dB}. Other parameters would typically have to be measured from the manufactured oscillator. Usually, an open stub (characteristic impedance of 50 ohms), which is terminated at the emitter end of the bipolar transistor, serves as the feedback element. By adjusting the electric length of the feedback stub, various port impedance in the band of interest can be obtained. This feedback element ensures that the stability factor of the active device is with enough margins less than unity. One important characteristics of a DRO is its phase noise at 10 kHz or higher away from the carrier. The phase noise of a DRO depends on the active device, the coupling to the DR, and the amount of power delivered to the load. The Si-bipolar transistor provides about a 10 dB improvement in phase noise, which is generally believed to be the contribution of V_{fm} noise of the GaAs FETs. Phase noise increases with the square of operating frequency [4]. As more energy is stored in the dielectric resonator, the temperature characteristic of the DRO more closely follows that of the DR, however much of the active device's power is dissipated in the DR, leaving less for output. Also the phase noise of the DRO may degrade. Therefore, some compromise must be made between the DRO's temperature stability and phase noise.

4.2 Computed and experimental results for dielectric resonator oscillator

Infineon's BFP420 is a high-performance, low-cost, Silicon-Germanium bipolar transistor housed in a 4-lead SOT-343 surface mount package. With a transition frequency in excess of 25 GHz, this device is ideal for high performance applications including low noise amplifiers and oscillators up to 10GHz. The BFP420 offers exceptionally low noise, high gain, high linearity and a low flicker-noise corner frequency. The BFP420 rivals in performances with more expensive GaAs FET devices, without requiring a negative supply voltage.

The schematic of the oscillator is presented in Fig. 3. The microstrip oscillator is placed on 0.635mm alumina substrate, with dielectric permittivity of 9.2. The dielectric resonator manufactured from ZST material has a dielectric constant of 36, a diameter of 13 mm and a height of 6 mm. It is used as a resonant circuit connected to the base of the bipolar transistor and coupled with a 50 Ω microstrip line. The line is terminated with a 50Ω resistor to avoid parasitic reflections. In this application the DR is tightly coupled in the $TE_{01\delta}$ mode to the input 50Ω microstrip line. This creates a very large resistance (i.e. open circuit) at the correct electrical distance from the transistor, causing oscillation. One advantage of using a DR as the input resonator is that the very high unloaded Qs of these devices (often on the order of 10000) yields an oscillator with little tendency to drift in frequency. As the resonator consists of an open circuit that is only coupled to the line at the oscillating frequency indicates that for other frequencies the transistor can be terminated on 50 Ω, reducing the possibility of secondary oscillations at undesired frequencies. The microwave signal is delivered from the transistor's collector to the 50 Ω load through a tapered matching line.

The oscillator behaviour is simulated using CAD software based on harmonic balance algorithm. The bias for the bipolar transistor is provided by a resistive network and a +5V power supply. The bias point of the transistor (I_C=18.3mA, V_{CE} = 3V and V_{BE} = 0.871V) is chosen for maximum P_{-1dB}.

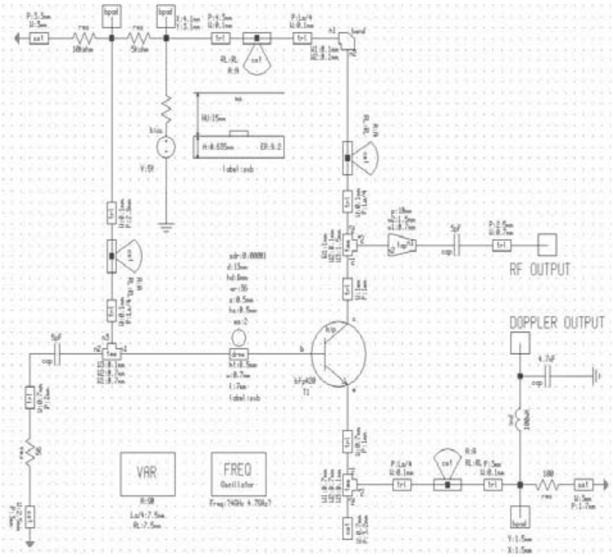


Fig. 3 DRO used as autodyne for Doppler sensor.

The output power spectrum is shown in Fig. 4

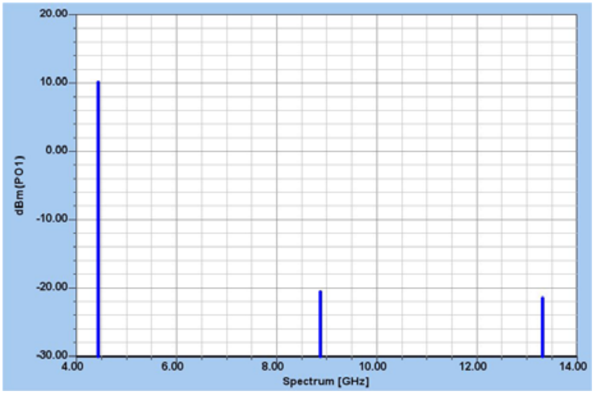


Fig. 4. Microwave signal power spectrum of the at the DRO output port.

The calculated frequency of oscillation is 4.43 GHz and the output power of the fundamental is +10 dBm, in good agreement with the level that would be predicted from the P_{-1dB} of the transistor (+12 dBm). The second and the third harmonics are less than -20dBm (50 dB below the fundamental power).

Fig. 5 shows the layout of the microstrip oscillator. The circuit is made on a 0.635mm alumina substrate using the Si-Ge bipolar transistor BFP420.

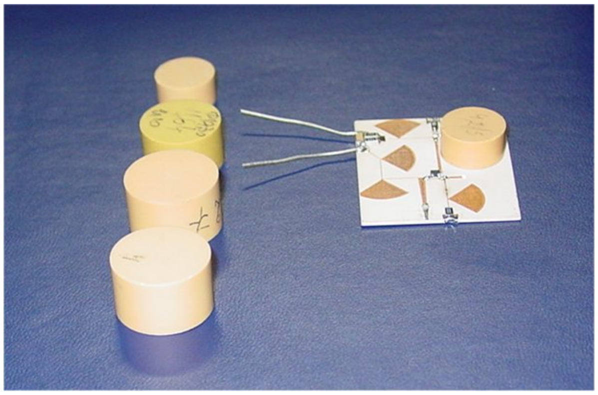


Fig. 5. Layout of the microstrip DRO and several ZST dielectric resonators.

Measurements on this oscillator show that the frequency of oscillation is around 4 GHz.

The design method of serial feedback oscillators based on S parameters was followed by computer simulations and optimisations. The optimisations criteria were the spectral purity and output power.

5. Radio proximity sensor with dielectric resonator from ZST material

The DRO oscillator analysed above can be transformed very easily into a radio proximity Doppler sensor. To this end an antenna has to be connected at the RF output and the Doppler signal picked up as shown in Fig. 3. The parameters of the antenna will be chosen as a function of the application.

In this configuration the oscillator behaves as an auto oscillating mixer. A low frequency signal is obtained by mixing the transmitted signal with the one reflected by the object. This signal is separated with a low pass filter having the cutting frequency higher than the maximum value of the Doppler frequency.

Antenna is connected in the collector of the transistor through a matching circuit. For experiments a monopole antenna ($\lambda/4$) had been used. It was fixed perpendicularly on microstrip circuit. Doppler signal is amplified in a low noise amplifier [5] which has a voltage gain of 80dB (10.000). Due to the high gain of the experimental model, special measure had been taken to ensure the electromagnetic compatibility.

The autodyne, Doppler amplifier and pulse shaping circuit are fed with separate voltage stabiliser from LM78** family. A 5 V voltage is used for feeding the autodyne, while the other two are fed with +15V. The use of different feeding circuit avoids the propagation of interference signals through different circuits of the radio proximity Doppler sensor. On the next picture the sensor is displayed.

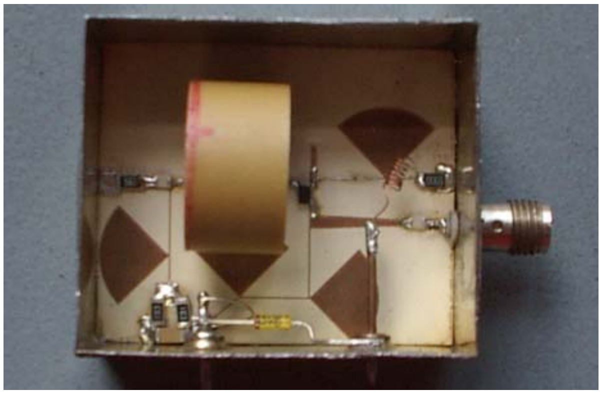
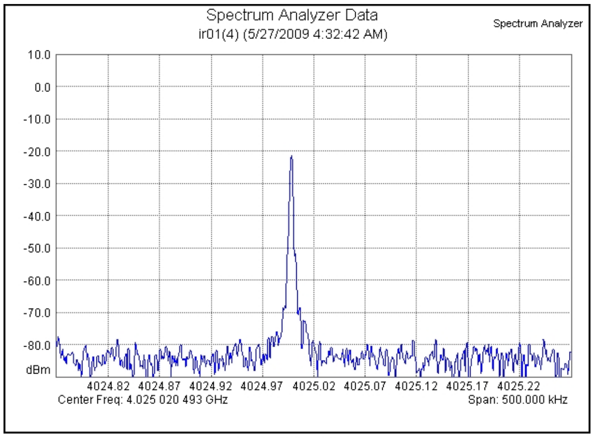


Fig. 6. Radio proximity Doppler sensor with DRO from ZST material.

Measurements on this oscillator show that the frequency of oscillation is around 4GHz.



Measurement Parameters

		Stop Frequency	4.025 270 GHz
Trace Mode	Normal	Frequency Span	500.000 000 kHz
Reference Level Offset	0.0 dB	Reference Level	10.000 dBm
Input Attenuation	30.0 dB	Scale	10.0 dB/div
RBW	1.0 kHz	Serial Number	829077
VBW	300.0 Hz	Base Ver.	V1.96
Detection	Peak	App Ver.	V3.14
Center Frequency	4.025 020 GHz	Date	5/27/2009 4:32:42 AM
Start Frequency	4.024 770 GHz	Device Name	

Fig. 7. Spectrum of the Doppler sensor measured with MS2724B spectrum analyzer (Anritsu).

In order to check how the sensor works, different measurements had been made. The output signal was measured using an oscilloscope TAS465 (Tektronix). A metallic plate 170x110mm^2 placed at 3 m apart of the sensor had been used as reflecting object. On the left side of the Fig. 8 the output signal of the sensor with no reflecting object is displayed while on the right the signal produced by hand moving of the metallic plate is pictured.

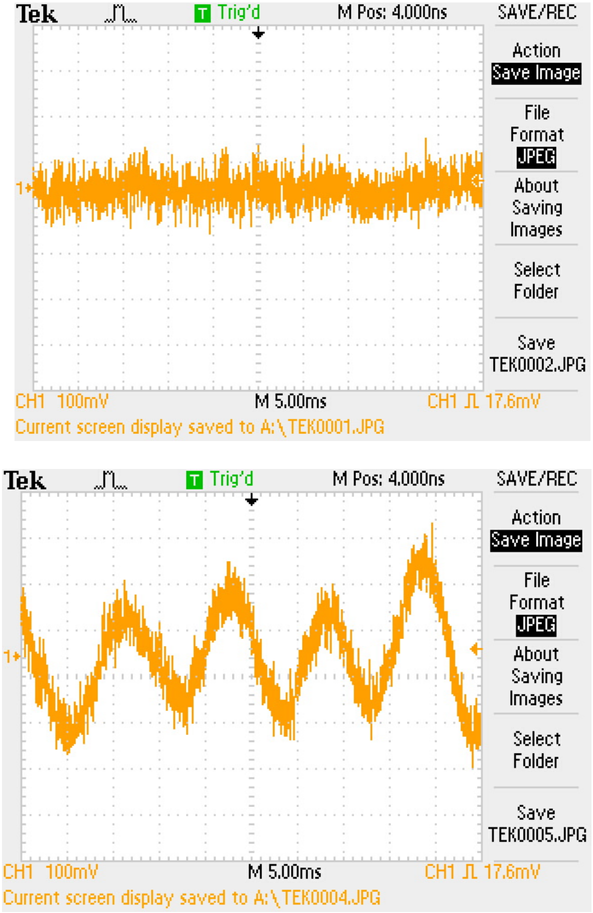


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Fig. 8. The signal at the output of the sensor with no reflecting object (left). Low frequency signal at the output of the low noise amplifier due to the hand moving of a 170X110mm^2 metallic plate (right).

The sensitivity of the sensor is quite high especially due to the low phase noise of the autodyne. The sensitivity can be improved if the autodyne is shielded and a directive antenna is employed instead of an omni directional one.

6. Conclusions

High permittivity dielectric materials are employed for passive microwave devices in order to decrease their physical dimensions. A new type of material, ZST, had been manufactured and used to build a DRO oscillator.

The feasibility of microwave oscillators with cylindrical resonators of ZST material was demonstrated. The high *Qxf* product of more than 50,000 allowed a low insertion loss for the resonant circuit. The oscillator has a low volume due to high ZST dielectric constant up to 36.8. Moreover, the resonance frequency temperature coefficient in the range of –4 to +4ppm/^{o}C provides a very good thermal stability of the oscillator.

Si Ge bipolar transistor (BFP420) has been used to design and fabricate sample oscillator. BFP 420 rivals in performances with more expensive Ga As FET devices, without requiring a negative supply voltage.

The oscillator can be easily turned into a Doppler sensor by adding an antenna and making it to work as an auto oscillating mixer. The Doppler signal is amplified and than used as a measure of the separation between the sensor and the object.

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[*] Corresponding author: ioannic@mta.ro