

Review of Some Types of Varactor Tuned DROs

Here is a summary of circuit design and construction of oscillators using dielectric resonators

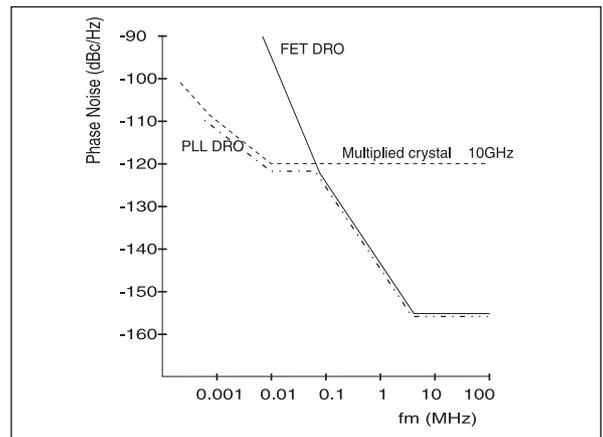
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Dielectric resonator oscillators (DROs) have a number of characteristics that distinguish them from other microwave generators, making them very popular in this field of technology. Only two characteristics, frequency stability and phase noise, are found to be better with crystal multiplier oscillators (Figure 1), however, phase noise of a DRO is lower at narrow band frequencies around the center frequency (<0.5 MHz) [1].

Generally, DROs are generators of stable frequency, but their center frequency is tunable within narrow limits (up to 1 percent f_c) by means of circuits that influence the electromagnetic field of a dielectric resonator (DR). Circuits with varactor diodes are most frequently used for center frequency tuning because they are simple and reasonably priced.

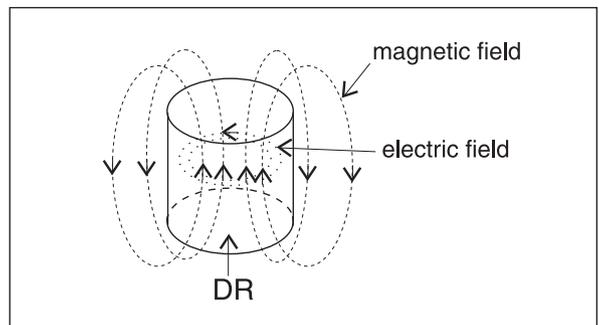
There are, however, some other methods to obtain this tuning. One method uses ferrite materials to control the magnetic field of a DR by the outer magnetic field [2, 3]. Another method uses a light source to change the conductivity of a photosensitive layer deposited on the top surface of a dielectric resonator, affecting field distribution of a DR [4]. A third method uses the oscillator characteristic to change its operating frequency with biasing voltage variation (pushing) [5, 6]. These methods are not frequently used in practice, because of specific disadvantages limiting their applications.

Circuits with varactor diodes are widely used in various commercial and military applications of voltage-controlled dielectric resonator oscillators. Such applications include temperature stabilization and modulation (FM) of voltage controlled oscillators used in PLL circuits for synchronization with referent oscillators.

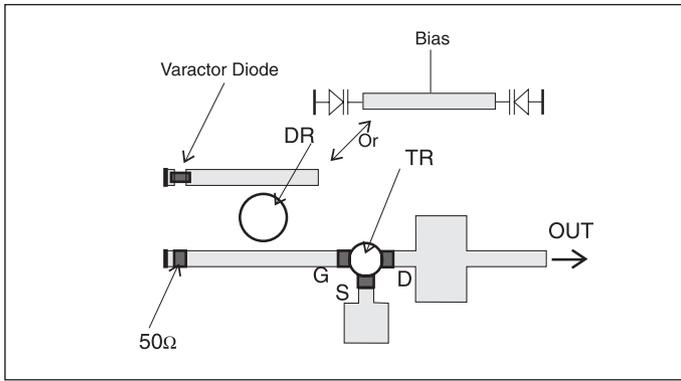


▲ **Figure 1. Comparison of phase noise performance of various oscillator configurations [1].**

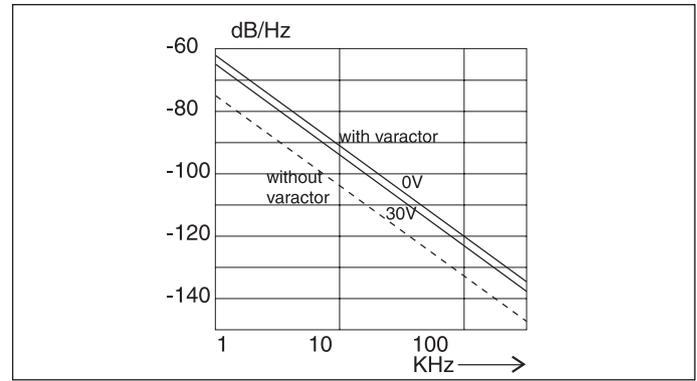
The main function of the diodes is the influence of their own electromagnetic field on the electromagnetic field of a dielectric resonator. As it is known, the electromagnetic field of a DR is mainly concentrated in a dielectric, but a small part is propagated into the immediate vicinity. This part of the electromagnetic field is



▲ **Figure 2. Dielectric resonator $TE_{01\delta}$ mode field distribution.**



▲ Figure 3. Varactor tuning of a reflection type DRO.



▲ Figure 4. Comparison of phase noise performance of various oscillator configurations [11].

important for achieving the electronic tuning of the DR's resonant frequency in an oscillator circuit. A dielectric resonator (Figure 2) has three dimensions, each permitting a circuit to be placed near a varactor diode. Circuits with varactor diodes can thus be placed laterally, under or on the dielectric resonator. Each of these circuits has both advantages and disadvantages, as we will discuss later.

Tuning circuit with varactor diode at the side of a DR

VCDRO tuned with a coupled microstrip line with a varactor — Examining a VCDRO with a DR that is electromagnetically coupled ($TE_{01\delta}$) to a microstrip line and varactor diode [6, 7, 8, 9], one will see that varying the varactor diode biasing voltage causes a change in the capacitance of the diode. The resonant frequency of the DR is coupled to the varactor-microstrip circuit on one side and to a 50 ohm line on the other side. A typical configuration of the oscillator is shown in Figure 3.

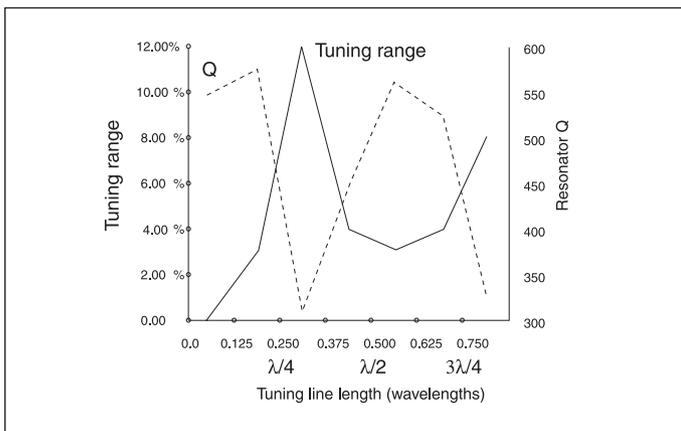
Tuning range of the equivalent DR's circuit resonant frequency and of the oscillator as a whole depends on the coupling of the circuit with varactor diode and a DR. Stronger coupling results in better frequency tuning. On the other hand, the Q factor as well as stability of the DR

decreases and FM noise increases. At these frequencies, the Q factor is important [10], while stronger coupling of the varactor diode circuit to the DR causes a degradation of the resonator's Q factor. Figure 4 shows noise with a frequency tuning of 0.1 percent at $f = 11$ GHz [11].

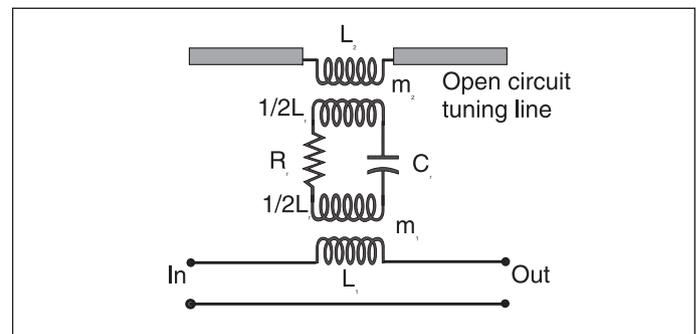
Besides the influence of the coupling strength between the tuning circuit and the DR, the microstrip line length influences the oscillator's frequency tuning. Usually, its length is about $\lambda_g/4$ and $\lambda_g/2$. However, interesting results have been published by K. V. Buer and E. B. El-Sharaway [12], showing that much better results can be obtained with non-resonant lengths of the tuning line, enabling greater frequency tuning and a lesser decrease of the Q factor. Frequency and Q factor tuning versus tuning line length (short-circuited at one end and open at the other end) is shown in Figure 5 [12].

The equivalent circuit shown in Figure 6 has been used to simulate the DR's behavior. It is coupled to the tuning circuit and varactor diode at one side, and to the microstrip line at the other side. Using this model, excellent experimental results have been obtained [12].

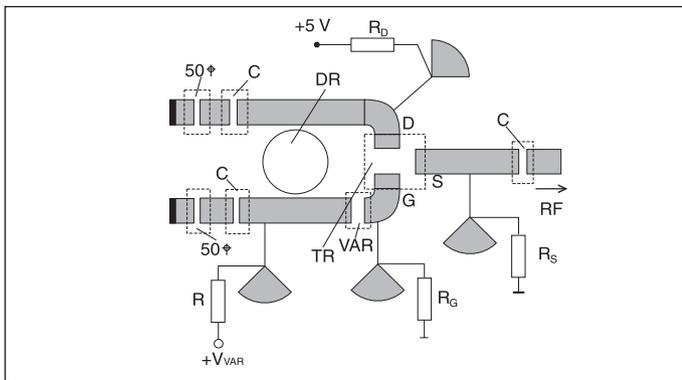
The oscillator's frequency tuning voltage versus varactor diode tuning voltage depends on the position of the varactor diode in the microstrip tuning circuit. Therefore, better linearity of this function can be achieved by proper placement of the varactor. This linearity also depends on the strength of the coupling with



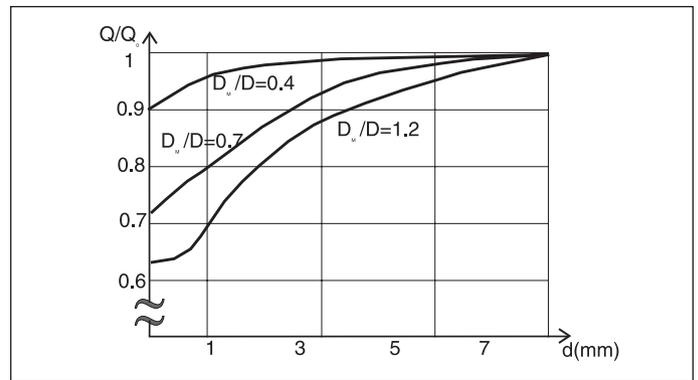
▲ Figure 5. Q factor and tuning range vs. length for microstrip tuning lines [12].



▲ Figure 6. Model of a dielectric resonator with microstrip tuning [12].



▲ Figure 7. Layout of the oscillator.

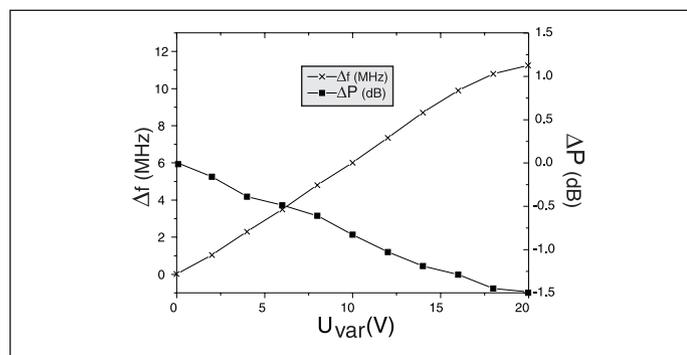


▲ Figure 8. Q factor characteristics of tuning structure with metal plate ($f_0 = 3.86$ GHz, $Q_0 = 4190$) [25].

the DR. On the other hand, greater frequency tuning (20 MHz/V at 42 GHz [13]) can be obtained by placing two diodes at the ends of the microstrip tuning line $\lambda_{g}/2$ long. Using a screw for fine mechanical frequency tuning, the central frequency of the oscillator can be independently tuned to a desired value.

VCDRO with varactor in the gate circuit — In the other circuit type, the varactor diode (beam-lead) is directly connected to the reaction circuit, which consists of gate and drain lines and a DR inductively coupled to them (Figure 7, [14]). Varying the voltage across the varactor changes the reactance and equivalent impedance of the whole reaction circuit, which determines the resonant frequency of the oscillator, 10.5 GHz.

Placing the varactor diode directly on the microstrip line of the gate, immediately to the gate's lead, the commonly-used separated circuit of the varactor is avoided and simple a design of the oscillator is created. It is clear that frequency tuning depends on the strength of the coupling between the DR and the gate line. Stronger coupling means greater frequency tuning. On the other hand, if the coupling between the DR and the drain line is stronger, the output power will increase and the electronic tuning range will be reduced. The ends of the gate and drain lines are terminated with stabilizing resistors (50 ohms), which prevent the occurrence of parasitic oscillations. A RF signal is taken from the source.

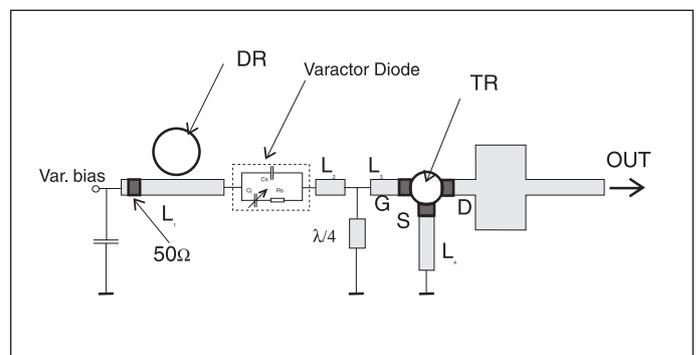


▲ Figure 9. Electronic tuning characteristics of the VCDRO.

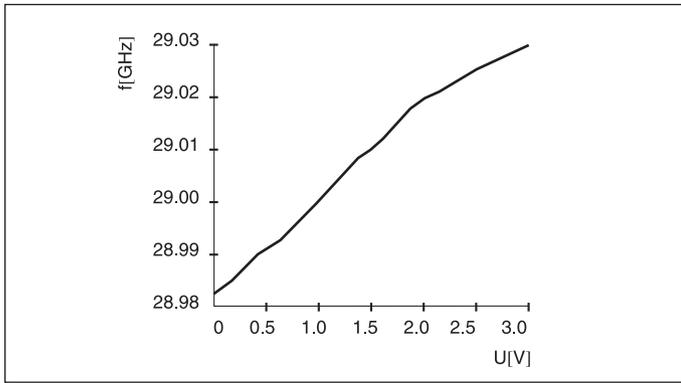
Mechanical frequency tuning obtained in this case is about 620 MHz (6 percent), while the microwave power variation is about 3 dB. It is unusual to go beyond the limit of 1 percent because within these limits there is no degradation of the Q factor. When the distance between the DR and the metallic screw is small (less than 2 mm), there is greater loss in the screw, due to induced currents. As a result, the total Q factor of the resonator decreases (Figure 8).

Variation of the output frequency of about 11.2 MHz (0.56 MHz/V), or 1 percent, was obtained with varactor diode biasing voltage variation from 0 V to 20 V. Output RF power varied within 1.5 dB. Figure 9 shows oscillation frequency and RF power of the oscillator versus biasing voltage of the varactor diode. This realization allows for a relatively simple oscillator circuit design, very similar to a corresponding DRO.

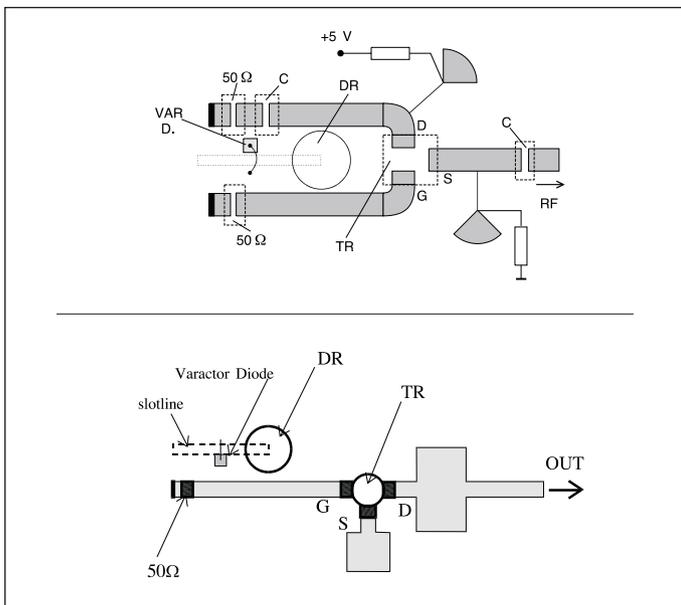
U. Guttich et al. [15] have achieved a frequency tuning of 45 MHz (15 MHz/V or 0.15 percent) at 29 GHz upon biasing voltage variation from 0 to 3 V using a similar design, but with a reflection-type oscillator (series feedback configuration) with a Schottky diode instead of a varactor diode (Figure 10). I. Takashi et al. [16] have applied a similar design at 60 GHz in MMIC technique with HJFET as a reactance element for frequency control, obtaining a frequency tuning of 34 MHz (55 MHz/V).



▲ Figure 10. Equivalent circuit of the DVO [15].



▲ **Figure 11. Oscillation frequency versus varactor tuning voltage U [15].**



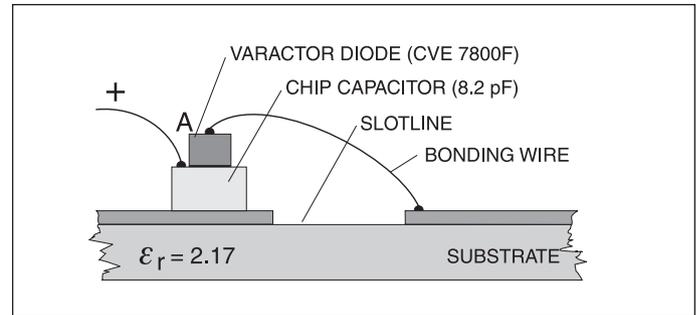
▲ **Figure 12. Oscillator configuration.**

Tuning circuit with varactor diode placed under the DR

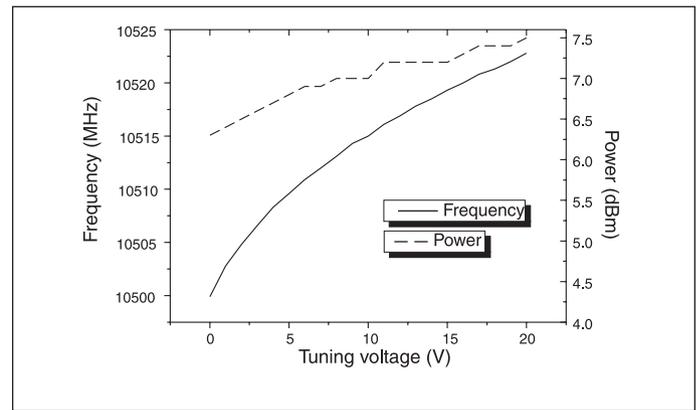
VCDRO Tuned with a slotline — The layout of the reaction type oscillator with a feedback through the DR, between gate and drain, at the oscillation frequency of 10.5 GHz is given in Figure 12a. The circuit for the voltage control of the oscillation frequency is magnetically coupled to the DR and placed on the lower side of the substrate, opposite of the side where microstrip lines of the oscillator circuit are. It has a slotline of $\lambda_g/2$ in length with one end positioned under the center of the DR [17].

The varactor diode is mounted across the center of the slotline and connects its sides (Figure 13). For DC biasing, the diode is decoupled from ground by a capacitor of 6.8 pF. Both the varactor diode and the capacitor are in the chip package, connected by gold epoxy bonding. Short bonding wire (to eliminate unneeded inductance) connects both sides of the slotline.

With a metallic screw above the DR and 0 V at the



▲ **Figure 13. Element mounting.**

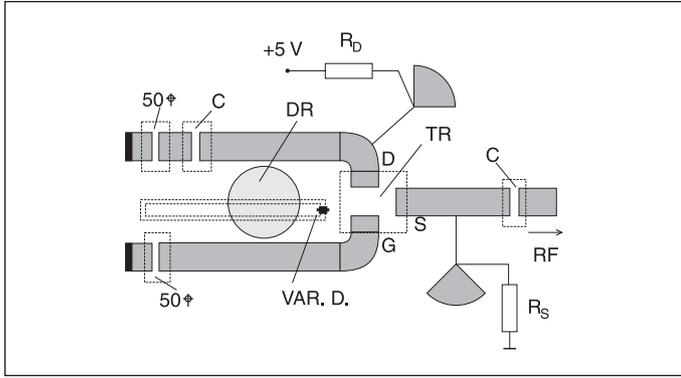


▲ **Figure 14. Power and frequency versus voltage across the diode.**

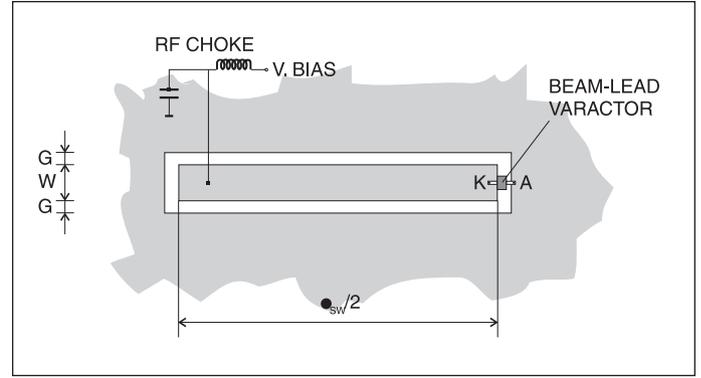
varactor diode, a mechanical frequency tuning of about 400 MHz (4 percent) is obtained. At the central frequency of 10.5 GHz (8 dBm) with the varactor diode voltage variation from 0 V to 20 V, a frequency tuning of about 28 MHz (1.4 MHz/V or 3 percent) is obtained. This is shown in Figure 14.

With the same tuning circuit (Figure 12b), but with a reflection type oscillator, J. B. de Swardt and P. W. Van Der Walt [18] have achieved a frequency tuning of 30 MHz at 12.66 GHz upon the varactor diode voltage variation from 2 V to 8 V (5 MHz/V). The magnitude of this frequency tuning depends on the length of the slotline and its proper positioning in the center of the DR. On the other hand, the position of the DR in relation to the microstrip line in the gate of the oscillator is not optional (it is determined by the oscillation condition of the oscillator). Thus, an optimization process to fulfill both of these conditions has to be performed, which is not easy without additional trimming and an understanding of new microstrip printed circuits.

VCDRO tuned by a CPW — The layout of an oscillator operating at 10.5 GHz with a tuning circuit is shown in Figure 15. The coplanar waveguide of $\lambda_g/2$ in length with a varactor diode (beam-lead) is placed on the metallization side under the dielectric resonator and inductively coupled to it. [19]. The tuning varactor diode is mounted at one end of the CPW, as shown in Figure 16.



▲ Figure 15. Oscillator configuration.



▲ Figure 16. CPW circuit for electronic frequency control of DRO.

Varying the varactor diode biasing voltage from 0 V to 20 V, a output frequency tuning of 7 MHz (0.35 MHz/V) is obtained while output RF power varies within 1 dB.

The configuration of the tuning circuit allows one more varactor diode to be mounted on the optimized CPW (on its other end), in case a greater sensitivity of frequency tuning is wanted. This is less dependent on the position of the DR than the previous setup (with the slotline). Also, its configuration is simple, reproducible and easy to fabricate.

Tuning circuit with varactor diode above the DR

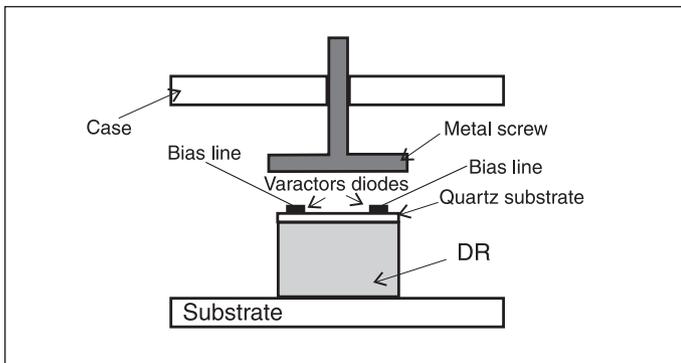
A tuning circuit with a varactor diode (or diodes) can be placed on the dielectric resonator [2], shown in Figure 17, or above it on the metallic tuning screw [20, 21, 22, 23], as shown in Figure 18.

A. N. Farr et al. [2] have proposed a solution with a quartz substrate disc where the resonant loop and two varactor diodes are placed, as shown in Figure 17. The quartz substrate disc itself is placed directly on top of the DR, as shown in Figure 19a. The resonant loop is electromagnetically coupled with the DR's field, influencing its oscillation frequency. With such a tuning circuit, a frequency tuning of about 60 MHz at 7.4 GHz (0.7 percent) and a Q factor greater than 1000 have been achieved upon the varactor diodes' biasing voltage variation from 0 V to 20 V (3 MHz/V). This allows relatively strong coupling, depending on the thickness of

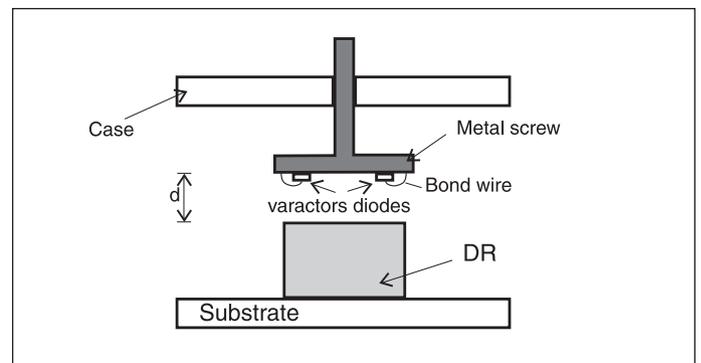
the quartz substrate. Some disadvantages of this design, however, include relatively complex mechanical structure, complicated varactor biasing and sensitivity to vibrations.

Another realization (Figure 18) involves placing the printed tuning circuit with the varactor diodes on the metallic screw for mechanical frequency tuning above the dielectric resonator [21, 22, 23]. It is simpler, less sensitive to vibrations and allows the coupling strength to change easily. Layouts of three different tuning circuits are shown in Figure 19.

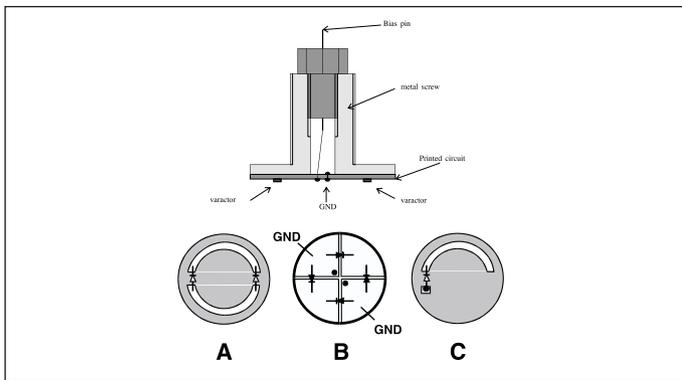
DRO realization with segments and PIN diodes (Figure 19b), proposed by A. Necic [21], is based on the perturbation of the field distribution above the resonator. The electric field of the DR induces surface currents in conducting segments. Elementary current-flow lines on the disc surface create a pattern similar to the electric field of the resonator. For the dominant $TE_{01\delta}$ mode, electric field lines have a concentric circles pattern and are similar to the pattern of induced currents on the disc surface. As the conducting disc is divided into segments, current-flow lines are cut and currents flow through PIN diodes. Changing the diodes' conductance causes change in the currents' intensities, which affects the structure of the disc electric field. Consequently, perturbation of the dielectric resonator field occurs and its resonant frequency changes. In this way, Necic has obtained a frequency tuning of about 40 MHz at 16 GHz



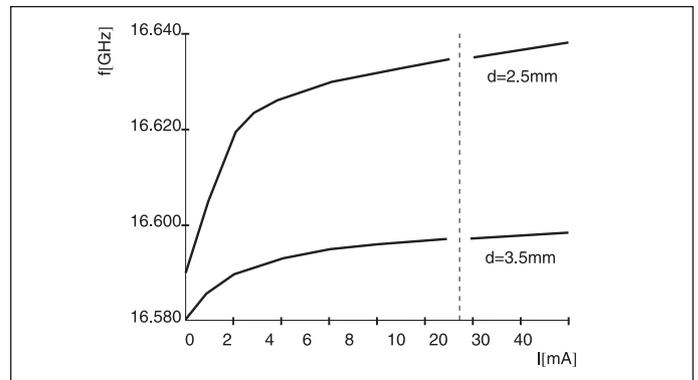
▲ Figure 17. Varactor placed on the dielectric resonator.



▲ Figure 18. Varactor placed above the dielectric resonator.



▲ **Figure 19. Metal screw (disc) with conducting segments (lines) and diodes.**



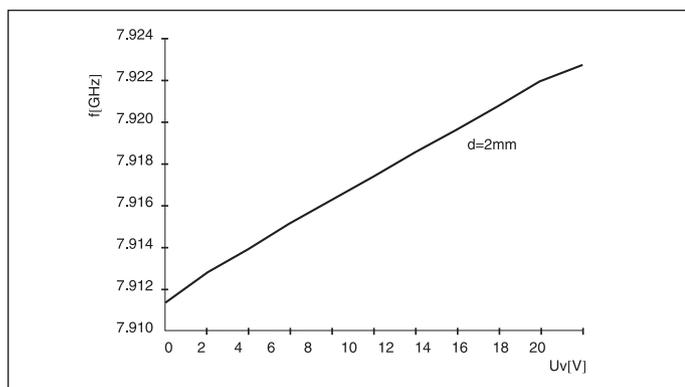
▲ **Figure 20. Frequency versus current through the diodes [21].**

(0.25 percent) upon the variation of the PIN diodes' current from 0 to 40 mA (Figure 20). The magnitude of frequency tuning depends on the distance between the segmented disc and the top surface of the dielectric resonator. The influence is greater if this distance is smaller. On the other hand, a smaller distance causes a decrease in the DR's Q factor and an increase in the oscillator's phase noise. Also, the small distance may cause the frequency to jump to a nearby higher mode.

A similar realization has been proposed by Z. Golubinic and V. Stoiljkovic [22], but with a varactor instead of PIN diodes. PIN diodes are current-driven and in certain applications, the driver circuit could be too complex and power consuming. Also, the Q factor of the DR significantly decreases because of the large equivalent resistance of the PIN diodes. Frequency tuning sensitivity is greater and linearity is worse than that of the corresponding circuit with varactor diodes.

With varactor diodes [22], a frequency tuning of about 30 MHz (0.37 percent) has been achieved at a frequency of 8 GHz upon the varactor voltage variation from 0 to 20 V (1.5 MHz/V).

Figure 21 shows frequency tuning at 7.9 GHz [22] versus voltage across the varactor diodes connecting the four segments that the disc is divided into. One may



▲ **Figure 21. Frequency versus voltage across the varactor diodes [22].**

notice that the curve is more linear than that of the realization with PIN diodes.

The magnitude of frequency tuning depends on the number of segments (minimum of 2), the disc radius, the diode capacity, their positions and the distance between the segmented disc and the DR. These must be taken into consideration in the optimization process and the circuit realization. Frequency tuning of 91 MHz (0.9 percent) at 10.4 GHz has been obtained on the varactor voltage variation (beam-lead) from 0 to 20 V (4.5 MHz/V) with the disc divided into two segments [23].

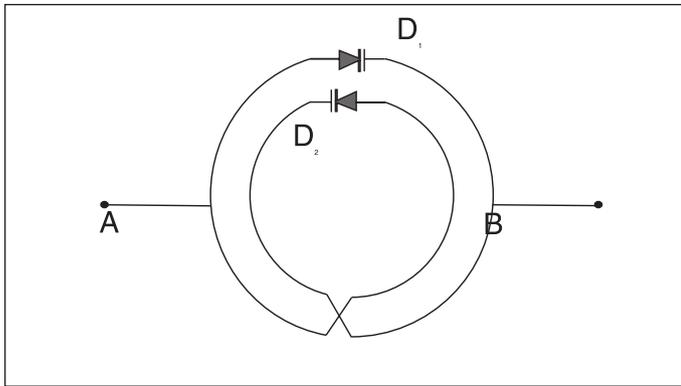
Instead of a segmented plate, a microstrip line with a length of between $\lambda_g/4$ and $3\lambda_g/4$, terminated with a varactor diode at one end [24], can be placed on the metallic screw, as shown in Figure 19c. This enables a change in coupling according to the required Q factor. Everything mentioned above concerning the coupled microstrip line with the varactor can also be applied in this case.

El-Moussaoui et al. [20] have obtained a frequency tuning of 3 MHz (0.3 percent) and the DR's unloaded Q factor of 9000 at a comparatively low microwave frequency (950 MHz) with a balanced loop placed above the DR (Figure 22).

Conclusion

This article is a review of several different methods of electronic frequency tuning of DRO's with varactor diode circuits, and an investigation of their influence on an oscillator's characteristics. With stronger coupling between the circuit, and with varactor diodes and a dielectric resonator, greater frequency tuning is obtained. However, an increase in the Q factor of the DR and an increase in phase noise occurs. Hysteresis and hopping from the TE_{018} mode for cylindrical resonators to some other close mode is also possible, followed by an abrupt change in resonant frequency.

The advantage of circuits with varactor diodes mounted on the tuning screw is the possibility of coupling tuning, but on the other hand, change in the cen-



▲ **Figure 22. Balanced-loop varactor [20].**

tral frequency is not independent (it depends on the position of the screw, i.e. strength of the coupling). Thus, a compromise must be made between the strength of the coupling, or the magnitude of the frequency tuning and the central frequency. However, a microstrip line with the varactor diode coupled to the dielectric resonator laterally and in the same plane with oscillator's circuit is a simple structure, independent of mechanical frequency tuning, but limited to coupling tuning, which results in insufficient electronic frequency tuning. Expected average frequency tuning achievable with these circuits in the X-band is between 5 MHz and 15 MHz, significantly lower than with circuits mounted above the DR and with a frequency tuning between 15 MHz and 30 MHz.

Circuits placed under the DR typically have stronger coupling, but their realization is more complex, especially in serial manufacture. The possibility of additional tuning is also restricted. Under similar conditions, the frequency tuning value achieved with these circuits is somewhere between those obtained with tuning circuits, where microstrip line is placed laterally, and tuning circuits placed above the DR.

In most applications of VCDRO, there is no need for extremely high frequency tuning (0.2 percent f_c is sufficient). This concerns applications in PLL circuits and circuits for both analog and digital temperature compensation. Greater frequency tuning is required when direct modulation is applied on a VCDRO. ■

Acknowledgment

The author wishes to thank Dr. A. Necic for a number of useful suggestions and I. Radnovic and N. Ipanovic for their assistance in translating this article into English.

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