Circuits with Varactor Diodes for Frequency Tuning in Dielectric Resonator Oscillators

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Introduction

Dielectric resonator oscillators (DROs) have a number of excellent characteristics distinguishing them from other microwave generators, which makes them very popular in this field. There are only two characteristics - frequency stability and phase noise - found to be better with crystal multiplier oscillators (Fig. 1). However, phase noise of a DRO is lower at frequencies out of narrow band around the central frequency (>0.5 MHz) [1].

Generally, DROs are generators of stable frequency, but their central frequency is tunable within narrow limits (up to 1% of f_c) by means of circuits that influence electromagnetic field of a dielectric resonator (DR).

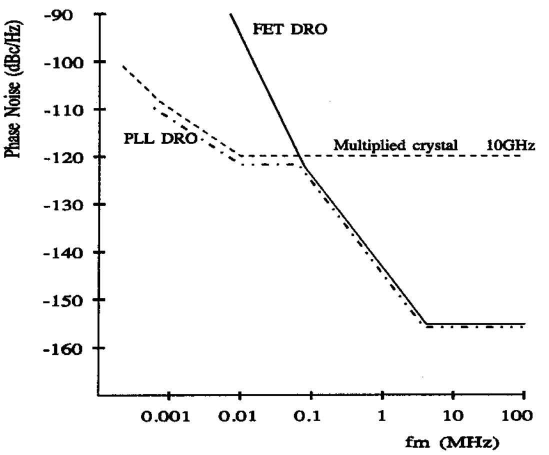


Fig. 1. Comparison of phase noise performance of various oscillator configurations [1].

Apart from central frequency tuning by circuits with varactor diodes that are most frequently used due to their simplicity and low cost, there are some other methods to obtain this tuning. One of them is the method which uses ferrite materials to control magnetic field of a DR by the outer magnetic field [2,3] and the other one - by using a light source to change the conductivity of a photosensitive layer deposited on the top surface of a dielectric resonator, which affects field distribution of a DR [4]. Also, there is a method that uses the oscillator characteristic to change its operating frequency with biasing voltage variation (pushing) [5,6]. Mentioned methods are not so frequently used in practice because of certain disadvantages limiting their application.

Circuits with varactor diodes are widely used in various commercial and military applications of VCDROs - from temperature stabilization or modulation (FM) to voltage controlled oscillators used in PLL circuits for synchronization with referent oscillators.

The main principle of their functioning is the influence of their own electromagnetic field on the electromagnetic field of a dielectric resonator. As it is known, electromagnetic field of a DR is mainly concentrated in a dielectric, but its smaller part is propagated out of it, in its immediate vicinity. This very part of the electromagnetic field is important for achieving the electronic tuning of the DR's resonant frequency in the oscillator circuit. Dielectric resonator (Fig. 2) has three dimensions and each of them permits close placing of a circuit with a varactor diode. So, circuit with varactor diode can be placed laterally, under or on the dielectric resonator. Each of these circuits, i.e. tuning methods has both advantages and drawbacks. An overview of them will be given in further text.

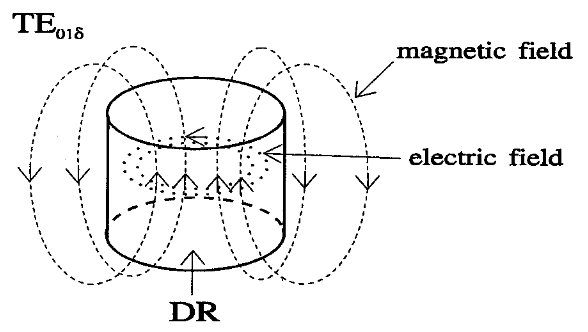


Fig. 2. Dielectric resonator $TE_{01\delta}$ mode field distribution.

Tuning Circuit with Varactor Diode Placed at the Side of a DR

VCDRO Tuned with Coupled Microstrip Line with a Varactor

One of the first VCDRO realizations was the realization of the oscillator with DR that is electromagnetically coupled ($TE_{01\delta}$) to a microstrip line and varactor diode [6,7,8,9,26,28,29]. Varying of the varactor diode biasing voltage causes the capacity change of the diode, i.e. resonant frequency of the DR coupled to varactor-microstrip circuit, on one side and with 50Ω-line, on the other side. A typical configuration of the oscillator is shown in Fig. 3.

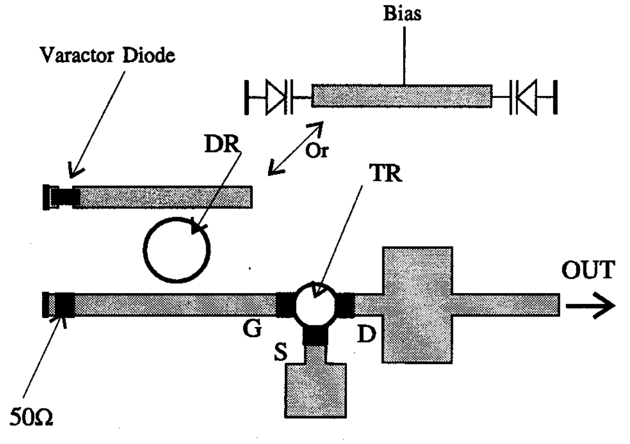


Fig. 3. Varactor tuning of a reflection type DRO.

Tuning range of the equivalent DR's circuit resonant frequency and thus of the oscillator as a whole depends on the coupling of the circuit with varactor diode and DR. Stronger coupling results in better frequency tuning. On the other hand, Q factor as well as stability of the DR decreases and FM noise increases. At these frequencies Q factor is important [10], while stronger coupling of the varactor diode circuit to the DR causes the degradation of the resonator's Q factor.

Figure 4 shows the influence of the varactor tuning on TDRO's FM noise with frequency tuning of 0.1% at f=11 GHz [11].

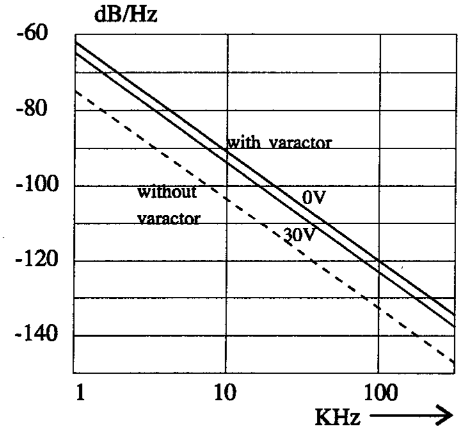


Fig. 4. Comparison of phase noise performance of various oscillator configurations [11].

Beside the influence of the coupling strength between tuning circuit and DR, there is an influence of the microstrip line length on the oscillator's frequency tuning. Usually, its length is about $\lambda_g/4$ and $\lambda_g/2$. However, very interesting results have been published by K. V. Buer and E. B. El-Sharawey [12] who have shown that much better results can be obtained with non-resonant lengths of the tuning line enabling greater frequency tuning and 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 given in Fig.5, [12].

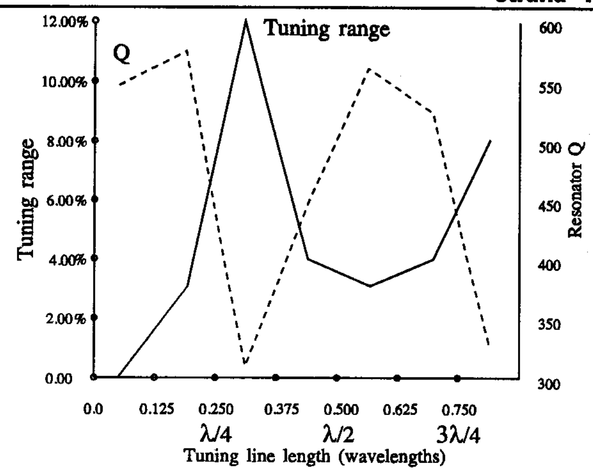


Fig. 5. Q and tuning range vs. length for microstrip tuning lines [12].

Equivalent circuit from Fig. 6. has been used in simulation of the DR's behavior which is coupled to the tuning circuit and varactor diode at one side, and microstrip line at the other side. Using this model, a very good agreement with experimental results has been obtained, [12].

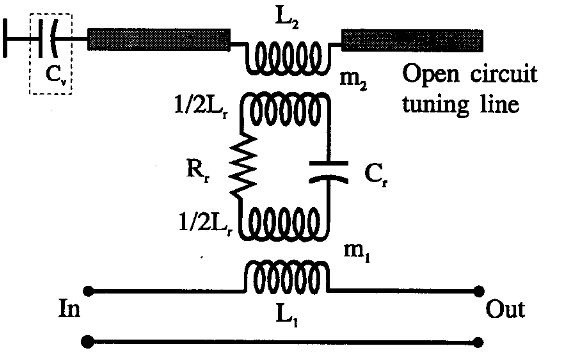


Fig. 6. Model of a dielectric resonator with microstrip tuning [12].

Frequency tuning of the oscillator versus varactor diode tuning voltage depends on the position of the varactor diode in microstrip tuning circuit, so better linearity of this function can be achieved by proper choice of the varactor's place. It should be mentioned that this linearity also depends on the strength of the coupling with 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 of length of about $\lambda_g/2$. Using a screw for a fine mechanical frequency tuning, central frequency of the oscillator can be independently tuned to desired value.

VCDRO with Varactor in the Gate Circuit

In the other circuit type, varactor diode (MA 46589, $C_j=2$ pF at 4 V, beam-lead) is directly connected with the reaction circuit which consists of gate and drain lines and a DR inductively coupled to them. (Fig. 7, [14]). Varying the voltage across the varactor, its reactance as well as equivalent impedance of the whole reaction circuit (which determines the resonant frequency of the oscillator - 10.5 GHz) changes.

Placing the varactor diode directly on the microstrip line of the gate, immediately to the gate's lead, commonly used separated circuit of the varactor is avoided and simple design of the oscillator is accomplished. It is clear that frequency tuning depends on the strength of the coupling between DR and the gate line, i.e. stronger coupling means greater frequency tuning. On the other hand, if the coupling between DR and drain line is stronger, the output power will increase and the electronic tuning range will be reduced.

Ends of the gate and drain lines are terminated with stabilizing resistors (50 Ω) which prevent occurrence of parasitic oscillations. RF signal is taken from the source.

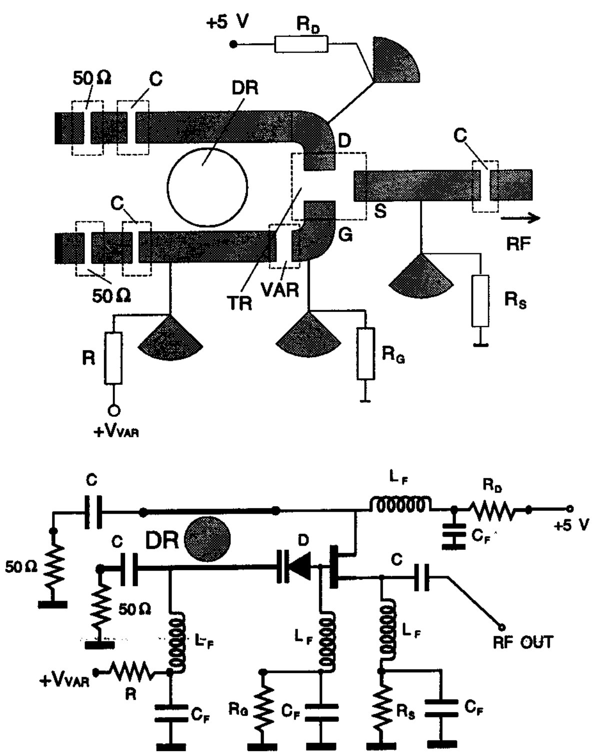


Fig. 7. Layout and circuit diagram of the oscillator.

Mechanical frequency tuning obtained in this case was about 620 MHz (6%), while microwave power variation was about 3 dB. However, it is not usual to go beyond the limit of 1% because within these limits there is no degradation of the Q factor.

Variation of the output frequency of about 11.2 MHz (0.56 MHz/V), i.e. 0.1% was obtained with varactor diode biasing voltage variation from 0 V to 20 V. Output RF power varied within 1.5 dB.

Figure 8 shows oscillation frequency and RF power of the oscillator versus biasing voltage of the varactor diode.

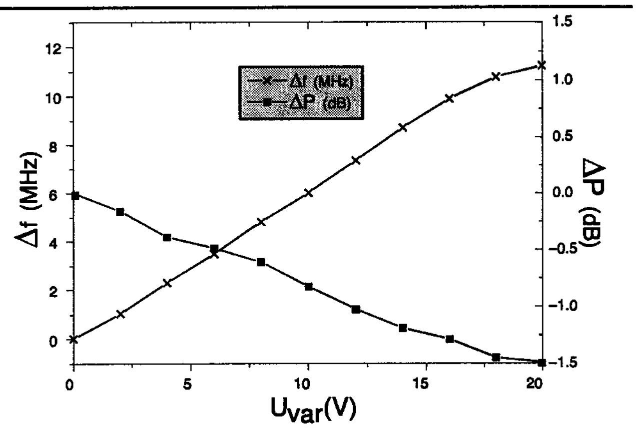


Fig. 8. Electronic tuning characteristics of the VCDRO.

The advantage of this realization is also relatively simple design of the oscillator circuit which is very similar to a corresponding DRO.

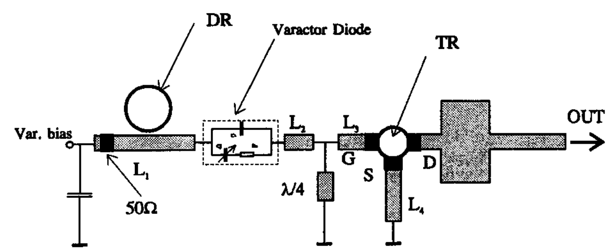


Fig. 9. Equivalent circuit of the DVO.

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

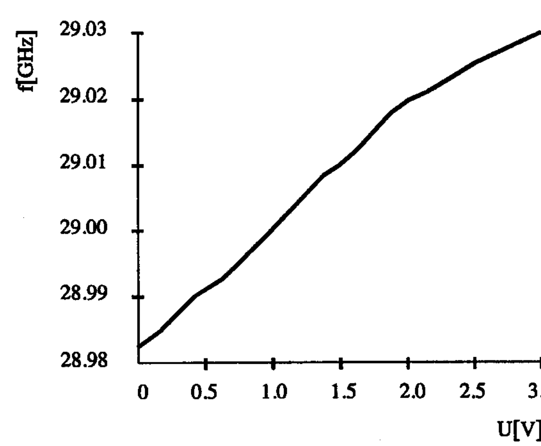
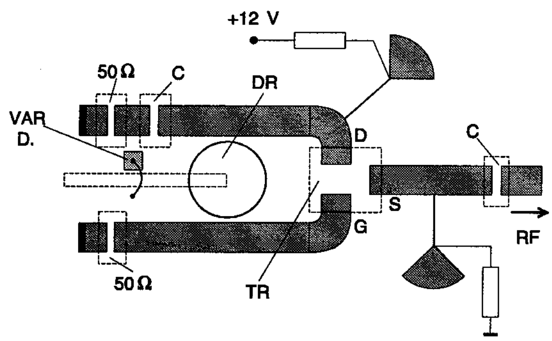


Fig. 10. Oscillation frequency versus varactor tuning voltage U [15].

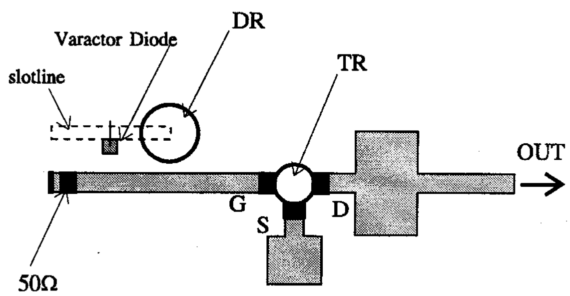
Tuning Circuit with Varactor Diode Placed under the DR

VCDRO Tuned with a Slotline

Layout of the reaction type oscillator with a feedback through DR, between gate and drain, at the oscillation frequency of 10.5 GHz is given in Fig. 11a. Circuit for the voltage control of the oscillation frequency is magnetically coupled to the DR and placed on the lower side of the substrate, i.e. opposite of the side where microstrip lines of the oscillator circuit are. It is realized as a slotline of $\lambda_s/2$ length with one end positioned under the center of the DR [17].



a)



b)

Fig. 11. Oscillator configuration.

Varactor diode is mounted across the center of the slotline and connects its sides. For DC biasing, diode is decoupled from ground by a capacitor of 6.8 pF. Both varactor diode and capacitor are in chip package and their connection is performed by gold epoxy bonding. Short bonding wire (to eliminate unneeded inductance) connects both sides of the slotline. Mounting of the elements is shown in Fig. 12.

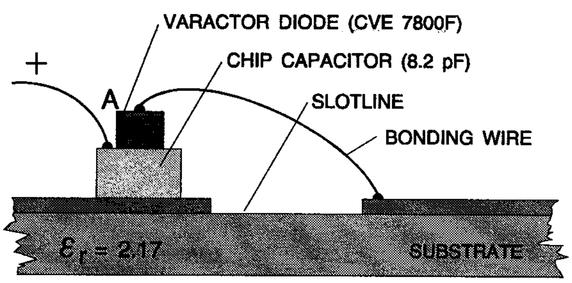


Fig. 12. Element mounting

With a metallic screw above the DR, upon the voltage of 0V at the varactor diode, mechanical frequency tuning of about 400 MHz (4%) is obtained. At the central frequency of 10.5 GHz (8 dBm) with varactor diode voltage variation from 0 V to 20 V, frequency tuning of about 28 MHz (1.4 MHz/V or 0.3%) is attained. This is shown in Fig. 13.

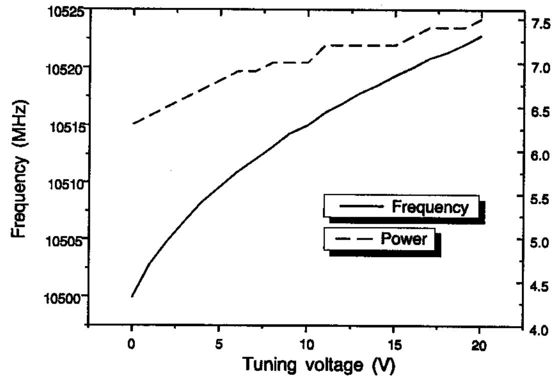


Fig. 13. Power and frequency versus voltage across the diode.

With the same tuning circuit (Fig. 11b), but with a reflection type oscillator, J. B. de Swardt and P. W. Van Der Walt [18] have achieved frequency tuning of 30 MHz at 12.66 GHz upon the varactor diode voltage variation from 2 V to 8 V (5 MHz/V). Magnitude of the frequency tuning depends on the length of the slotline and its proper positioning in the center of the DR. On the other hand, 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). So, an optimization process to fulfill both of these conditions has to be performed, which is not easy without additional trimming and realization of new microstrip printed circuits.

VCDRO Tuned by a CPW

Layout of the oscillator operating at 10.5 GHz with a tuning circuit is shown in Fig. 14. The coplanar waveguide (w=1 mm, G=0.2 mm, ε_r=2.17, h=0.25 mm) of $\lambda_g/2$ length with varactor diode (MA 46589, C_j=2 pF at 4 V, beam-lead) is placed on the metallization side under the dielectric resonator and inductively coupled to it. [19]. Tuning varactor diode is mounted at one end of the CPW, as shown in Fig. 15.

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

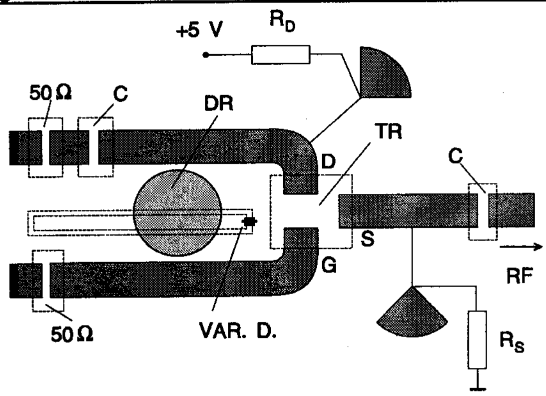


Fig. 14. Oscillator configuration.

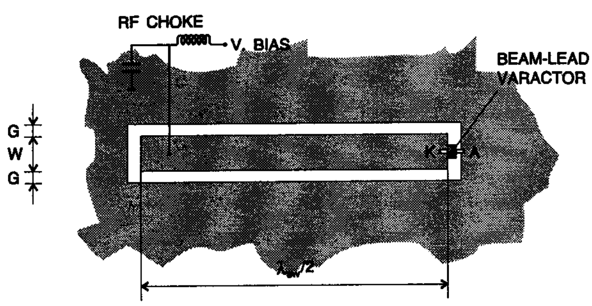


Fig. 15. CPW circuit for electronic frequency control of DRO.

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

Tuning Circuit with Varactor Diode Above the DR

Tuning circuit with varactor diode (or diodes) can be placed on the dielectric resonator [2], Fig. 16, or above it [20] - on the metallic tuning screw [21, 22, 23], Fig 17.

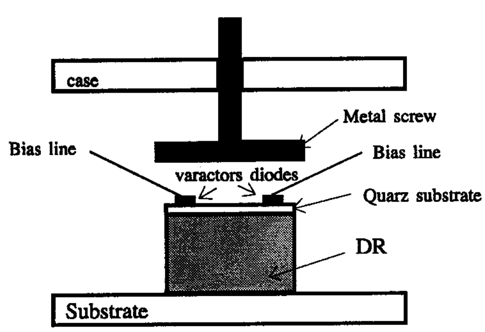


Fig. 16. Varactor placed on the dielectric resonator.

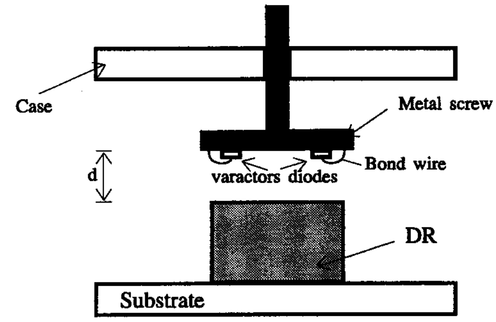


Fig. 17. Varactor placed above the dielectric resonator.

A. N. Farr et al. [2] have proposed the solution with quartz substrate disc where resonant loop and two varactor diodes are placed, Fig. 16. The quartz substrate disc itself is placed directly atop the DR, Fig. 18-A. Resonant loop is electromagnetically coupled with DR's field influencing its oscillation frequency. With such tuning circuit, frequency tuning of about 60 MHz at 7.4 GHz (0.75%) and Q factor greater than 1000 have been achieved upon varactor diodes biasing voltage variation from 0 V to 20 V (3 MHz/V). Advantage of this realization is relatively strong coupling which depends on the thickness of the quartz substrate and disadvantages are relatively complex mechanical structure and complicated varactor biasing as well as sensitiveness to vibrations.

Another realization (Fig. 17) which involves placing of the printed tuning circuit with varactor diodes on the metallic screw for mechanical frequency tuning above the dielectric resonator [21, 22, 23] is more simple, less sensitive to vibrations and allows easy changing of the coupling strength. Layouts of three different tuning circuits are shown in Fig. 18.

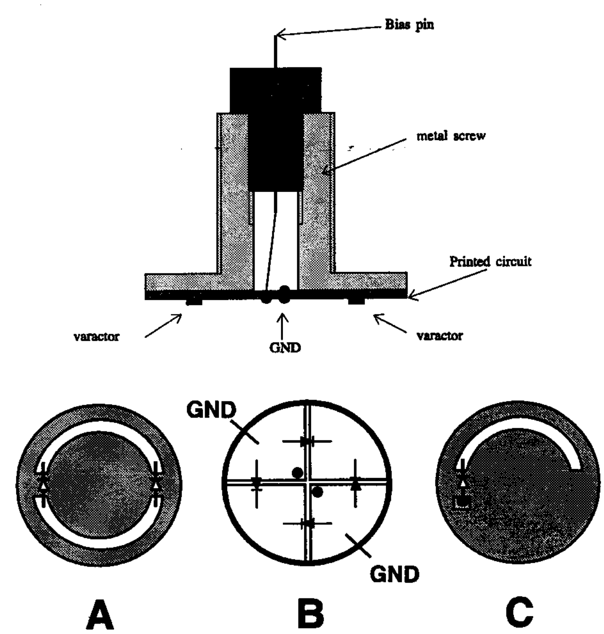


Fig. 18. Metal screw (disc) with conducting segments (lines) and diodes.

Realization with segments and PIN diodes (Fig. 18-B), proposed by A. Nešić [21], is based on perturbance of the field distribution above the resonator. 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 dominant $TE_{01\delta}$ mode, electric field lines have the concentric circles pattern and alike is 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 of the diodes' conductance causes the change of the currents' intensities, which affects the structure of the disc electric field. As a consequence of this, perturbance of the dielectric resonator field occurs and its resonant frequency changes. In this way, A. Nešić has obtained frequency tuning of about 40 MHz at 16 GHz (0.25%) upon the variation of PIN diodes' current from 0 to 40 mA (Fig. 19). 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, smaller distance causes decrease of DR's Q factor and increase of the oscillator's phase noise. Also, hopping in (to) some other higher close mode is possible.

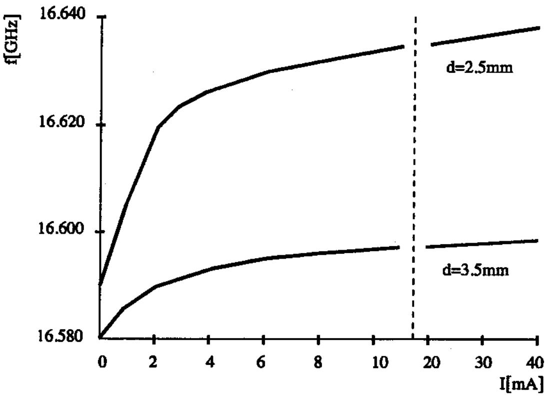


Fig. 19. Frequency versus current through the diodes [21].

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

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

Fig. 20 shows frequency tuning at 7.9 GHz [22] versus voltage across the varactor diodes connecting four segments that disc is divided into. We can notice that the curve is more linear than that of the realization with PIN diodes.

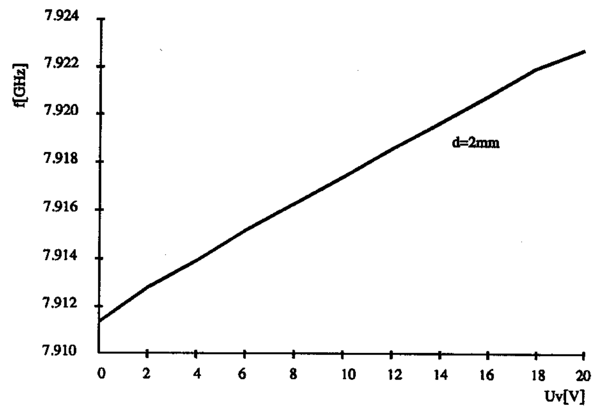


Fig. 20. Frequency versus voltage across the varactor diodes [22].

Magnitude of frequency tuning depends on the number of segments (minimum 2), disc radius, diode capacity, their position and the distance between segmented disc and DR. These must be taken in consideration upon optimization process and circuit realization. Frequency tuning of 91 MHz (0.9%) at 10.4 GHz has been obtained upon the varactor voltage variation ($C_{j\text{-}4V}=2$ pF, beam-lead) from 0 to 20 V (4.5MHz/V) with disc divided into two segments [23].

Instead of a segmented plate, a microstrip line of length between $\lambda_g/4$ and $3\lambda_g/4$ terminated with varactor diode at one end [24] can be placed on the metallic screw, as shown in Fig. 18c. This enables change of coupling according to required Q factor. Everything mentioned above concerning the coupled microstrip line with varactor can also be applied in this case.

El-Moussaoui et al. [20] have obtained frequency tuning of 3 MHz (0.3%) and DR's unloaded Q factor of 9000 at comparatively low microwave frequency (950 MHz) with balanced loop placed above the DR (Fig. 21).

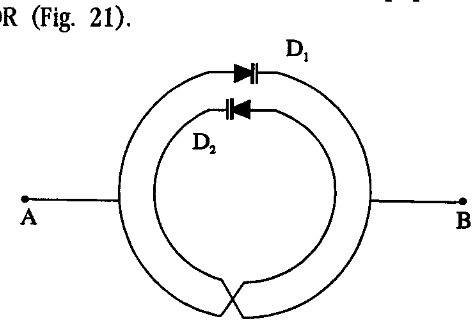


Fig. 21. Balanced-loop varactor.

Conclusion

This paper is a review of several different methods of electronic frequency tuning of DRO's with varactor diode circuits with an investigation of their influence on oscillator's characteristics. With stronger coupling between the circuit with varactor diodes and dielectric resonator, greater frequency tuning is obtained. However, increase of Q factor of the DR and increase of phase noise occurs. Hysteresis and hopping from $TE_{01\delta}$ mode for cylindrical resonators to some other close mode is also possible which is followed by abrupt change of resonant frequency.

Advantage of circuits with varactor diodes mounted on tuning screw is the possibility of coupling tuning, but on the other hand, change of the central frequency is not independent (it depends on the position of the screw, i.e. strength of the coupling). So, a compromise must be made between the strength of the coupling, i.e. magnitude of frequency tuning and the central frequency. However, microstrip line with varactor diode coupled to dielectric resonator laterally and in the same plane with oscillator's circuit is a simple structure, independent mechanical frequency tuning, but limited coupling tuning which results in insufficient electronic frequency tuning. Expected average frequency tuning achievable with these circuits in X-band is between 5 MHz and 12 MHz, which is significantly lower than that with circuits mounted above the DR having the 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. Possibility of additional tuning is also restricted. Under similar conditions, 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% 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 VCDRO.

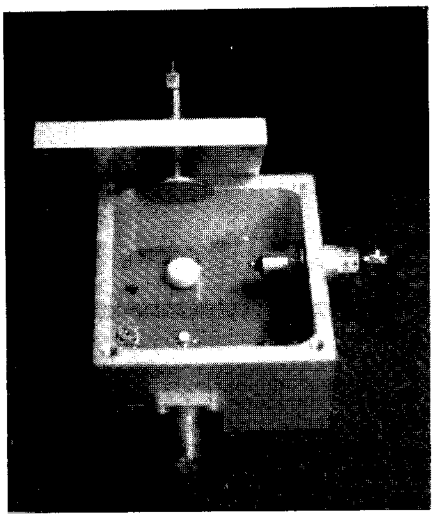


Fig. 22. Photograph of the realized DRO with varactor placed on the tuning screw.

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