Ulrich L. Rohde, PhD, N1UL
990 Cape Marco Dr, Merida Penthouse 2, Cape Marco, FL 34145; KA2WEU@aol.com

From Spark Generators to Modern VHF/UHF/SHF Voltage Controlled Oscillators

Here is a brief overview of RF oscillators — from Heinrich Hertz's original apparatus to modern voltage controlled oscillators.

As we teach advances in the field of microwave oscillators, it may be fun to step back and look at the origin of oscillators. The very first one, invented by Heinrich Hertz in 1886, was generating RF energy based on a spark across a gap, and used a resonant dipole as a frequency determining element.

The original test circuit shown in Figure 1 is preserved at the Deutsche Museum in Munich, Germany. Figure 2 shows the current and voltage distribution along the dipole.[1, 2]

The iron balls at the end of the 2 wires, as shown in Figure 2, reduce the resonant frequency significantly. Today we call this capacitive loading, and this also makes the dipole bandwidth much narrower. Since the gap between the two poles produces a high impedance, the transmissions result in a highly damped waveform. A better way to show this and duplicate the result is by using a four-gap spark "transmitter" based on the 1914 work of Leimbach, as shown in Figure 3. Probably the most efficient of these "arcing" transmitters was the one built by Ludena in 1929, as shown in Figure 4.

These spark "oscillators" were driven by a modulated voltage, resulting in a hum-like sound at the receiving station.

Progress was made in the following years by the invention of an electron tube in about 1932 that was suitable for microwave applications. While the tube was one of the requirements of the oscillator, the resonant circuit was another important part of the circuit. In 1935, so called acorn tubes (miniature triode tubes) were developed, and probably the very first "crystal" triode transmitter was configured. This is shown in Figure 5.

[1]Notes appear on page 45.

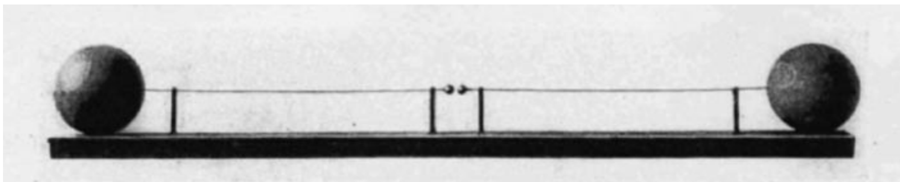

Figure 1 — Original dipole made by Heinrich Hertz in 1887 using balls at the end to form a capacitive load (Deutsches Museum, Munich) See Note 1.

Rather than getting the energy from a spark, the next generation of oscillators consisted of an amplifier with feedback, where a small amount of energy is used to start the oscillation, and then maintain the oscillation. Today, this is explained in terms of a negative resistance, which compensates for the losses, and can be expressed by concentrating them in the form of a loading resistor in parallel with the resonator (tuned circuit). By applying the right amount of feedback, the input (and/or output) of the amplifier shows a negative parallel impedance (or a transformed negative series impedance). Equation 1 is a simplified equation using the familiar Y-parameters, but can also be expressed in other forms, such as S-parameters. I prefer the Y parameters since they give more insight into the circuit than other forms.

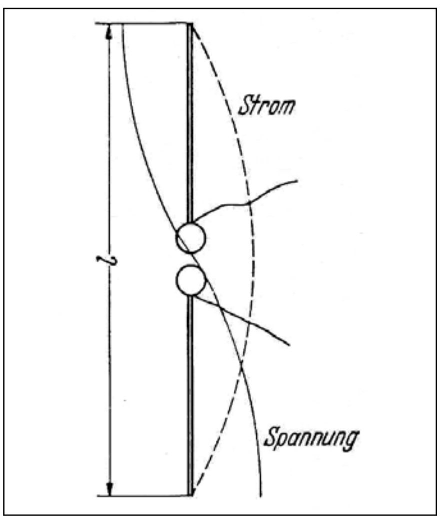

Figure 2 — A typical current (strom) and voltage (spannung) distribution along the length of the Hertz dipole. See Note 1.

$$Y^* = \frac{Y_{21} \times Y_{12}}{Y_{22} + Y_L}; \quad Y^* < 0$$

Y_{21} is the forward transconductance,

Y_{12} is the reverse tranconductance (internal and external feedback)

Y_{22} is the output conductance, and

Y_{11} is the input conductance of the active device (tube or transistor).

Y_L is the output with load.

In the beginning, the capacitively loaded dipole determined the resonant frequency, and soon after discovering the piezoelectric effect, turmaline crystals, of all things, were used to stabilize the oscillator frequency. This is shown in Figure 5. This is a photograph of probably the first stable " crystal controlled," slightly tunable 455 MHz oscillator. (See Note 1.)

In the search for stable but tunable resonators, the principle of a quarter wave line was applied. By mechanically tuning the inner portion of a coaxial resonator, a high Q (Figure of merit, ratio of stored energy versus dissipated energy) oscillator with the novel mechanical arrangements shown in Figure 6 were invented. (See Note 2.) In the case shown in Part A, a screw allows fine tuning while in Part B the end can be mechanically set over a wide range. An actual circuit diagram is given in Figure 7, which shows how the tube is connected. (See Note 2.)

This system for obtaining very good resonators was applied to test equipment, where tuning the mechanical resonator set the oscillator frequency. This oscillator was used in the early Tektronix spectrum

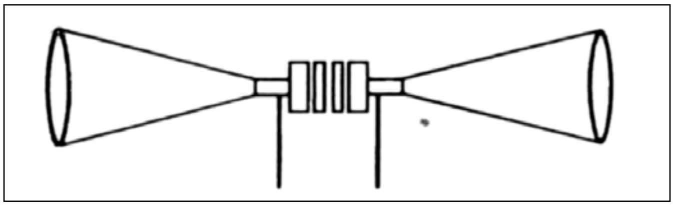

Figure 3 — Thick dipole formed by two conical resonators with spark gap (1914). See Note 1.

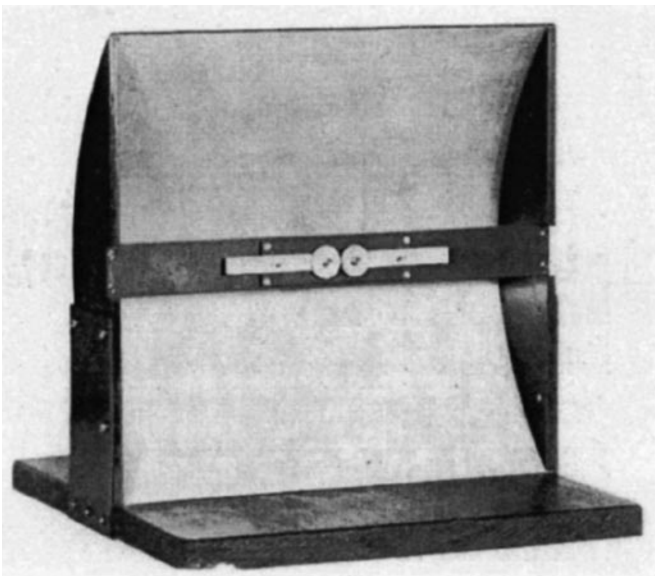

Figure 4 — Dipole oscillator with parabolic mirror (1929). (See Note 1.)

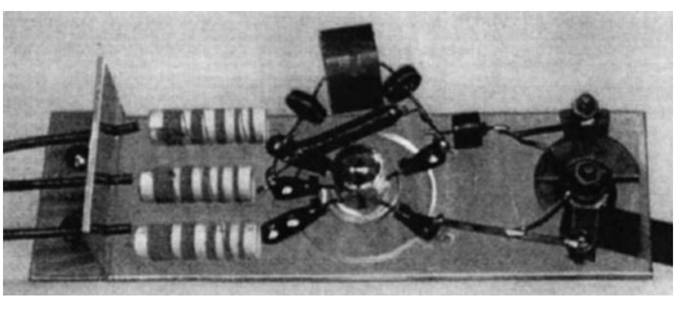

Figure 5 — 455 MHz crystal triode transmitter. (See Note 1.) The leads come out the sides of this "lighthouse" tube. Notice the three RF chokes on the left.

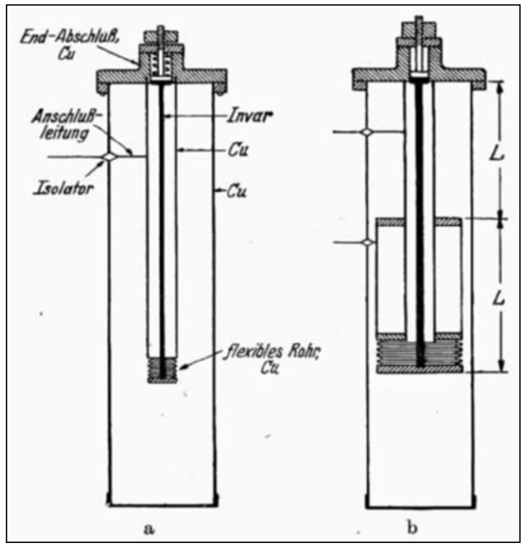

Figure 6 — Coaxial resonator oscillators. (See Note 2.) Invar refers to a type of steel used for the center conductor.

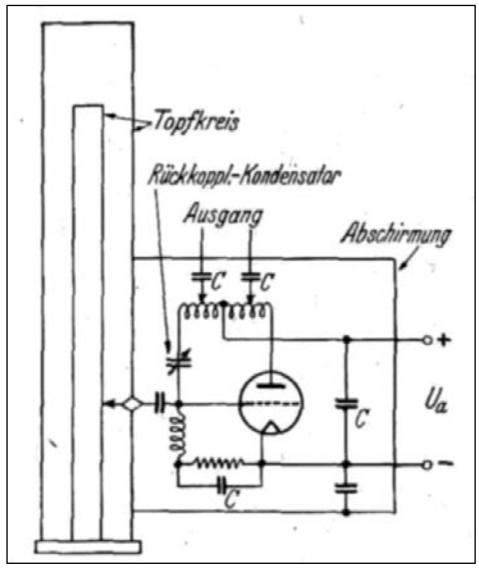

Figure 7 — Actual early tube oscillator circuit using a coaxial resonator. (See Note 2.) Topfkreis means coaxial resonator, Rückkappl-Kondensator refers to the tuning capacitor, Ausgang refers to output capacitors and Abschirmung is a shielding box.

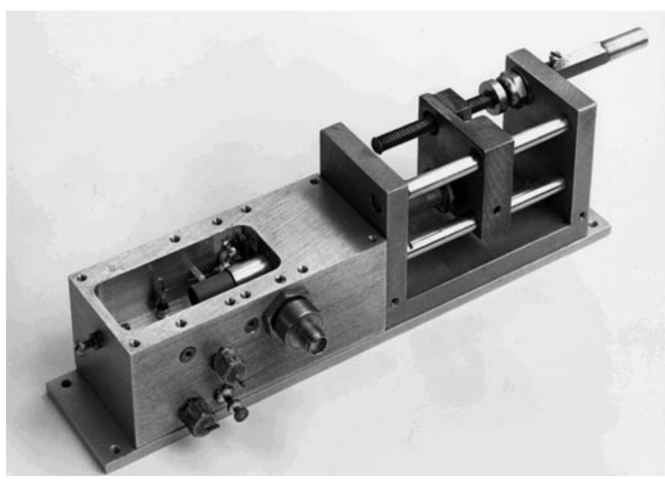

Figure 8 — Mechanically tuned 4GHz transistor oscillator.[3] The tuning shift is on the right side.

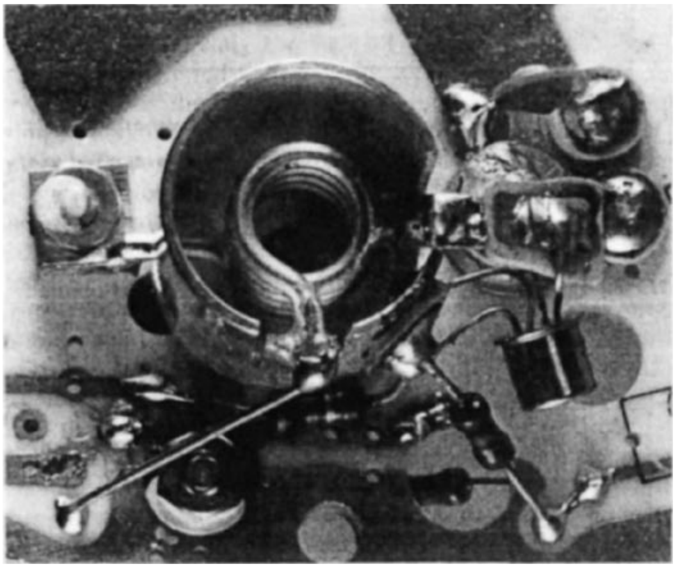

Figure 9 — High Q helical resonator oscillator (Rohde & Schwarz, SMDU).[4] Notice the transistor hanging off the right side of the resonator.

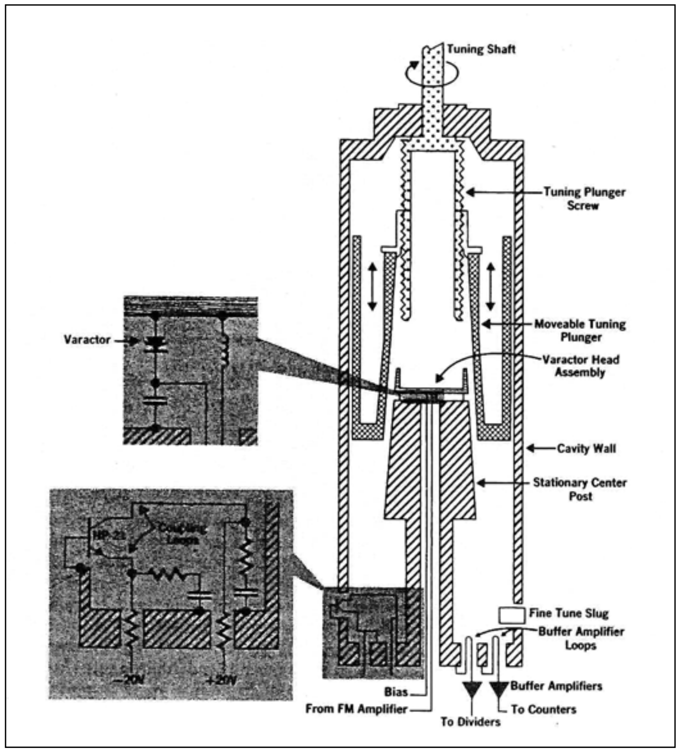

Figure10 — Mechanically tuned 200 to 400 MHz Oscillator (Hewlett Packard HP8640).

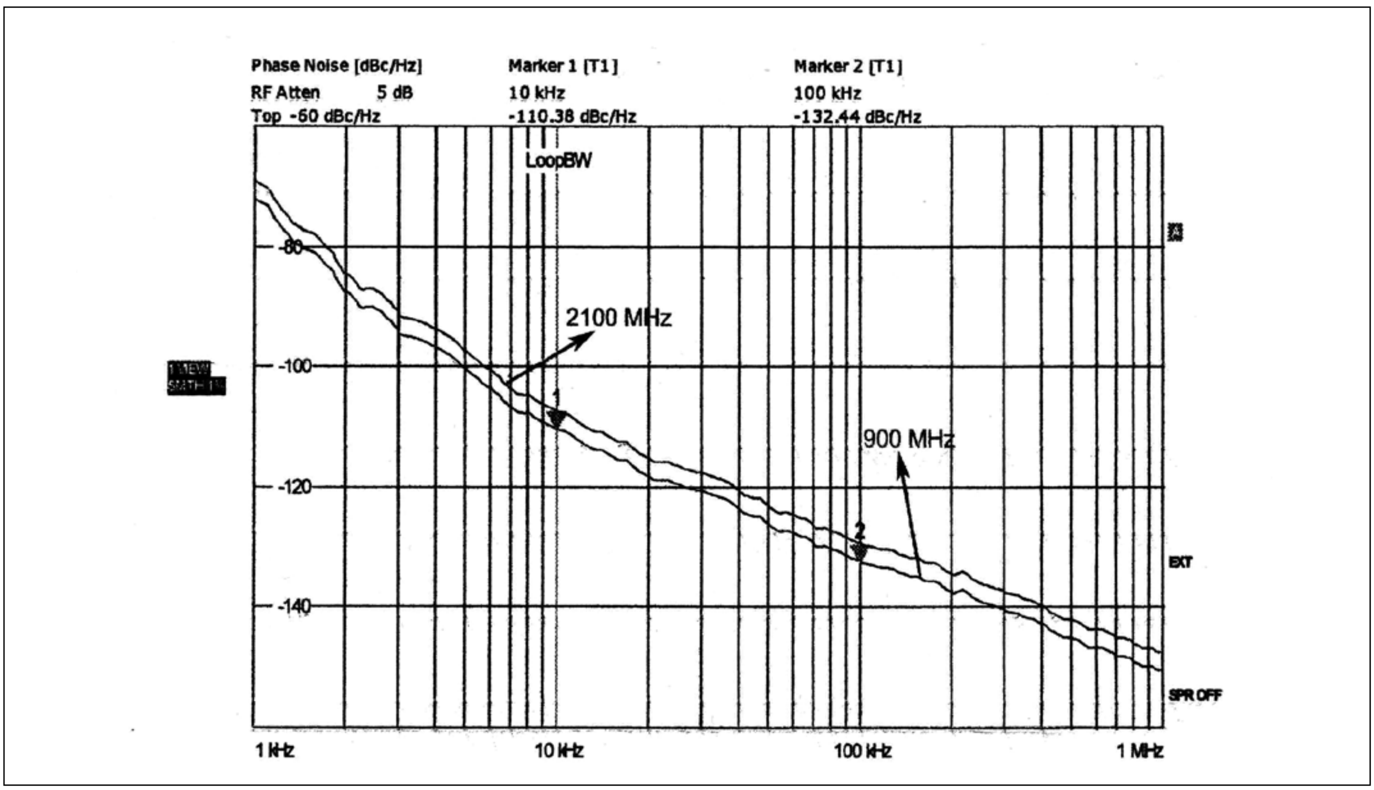

Figure 11 — Measured phase noise of a modern coupled mode resonator (line) based wideband VCO (900-2100 MHz) (Synergy Microwave Corp, USA).

analyzers, where the actual frequency was modulated as part of a phase locked loop control system, which stabilized the frequency against a standard. The photograph of Figure 8 shows the mechanically tuned resonator and the oscillator circuit. (See Note 2.)

A variation of this is the helical resonator, which has a high Q, low radiation and needs to be tuned electrically by some mechanical device — in this case an air variable capacitor. This was done in the vintage 1970 Rohde & Schwarz SMDU signal generator (Figure 9). Hewlett Packard — now Agilent — designed their HP 8640 signal generator around the tunable cavity, 200 to 400 MHz, and dividing the output frequency down for lower frequency in segments of 2:1. These were built when the spectral purity of a (wide) tunable oscillator became interesting. This parameter is called phase noise, expressed in dB below the carrier in different offsets referenced to 1 Hz bandwidth.

Today, with synthesized signal generators, these mechanical systems are replaced by voltage controlled oscillators (VCOs), using tuning diodes or varactors. These are reverse biased Si or GaAs diodes, which become voltage dependent semiconductor capacitors with a variation of up to 10 times change of the capacitance. These oscillators are built around printed circuits, which have a Q of about 50 for the resonators. By applying modern 3D field theory of coupled lines and resonators, these modern marbles now realize a Q of up to 250, and compete well with the previous mechanical designs. They meet the stringent requirements of a modern wide tunable system with good phase noise. Figure 11 shows the measured phase noise of a modern coupled mode resonator (line) based wide band VCO and Figure 12 shows the phase noise of a 1960 vintage tube mechanically tuned oscillator (R&S). The layout of the modern printed resonator using this patented design is shown in Figure 13.[5, 6, 7, 8, 9, 10]

For more details on these oscillators see the references and **www.synergymwave.com**.

Notes

[1]H. E. Hollmanm, *Physik und Technik der ultrakurzen Wellen*, Verlag von Julius Springer, Berlin 1936.

[2]H. Rothe and W. *Kleen, Elektronenöhern Als Schwingungserzeuger und Gleichrichter*, Akademische Verlagsgesellschaft Becker & Erler Kom.— GES, Leipzig, 1941.

[3]G. Vendelin, A. Pavio, U. L. Rohde, *Microwave Circuit Design Using Linear and Nonlinear Techniques*, Second Edition. John Wiley & Sons, Inc 2005.

[4]U. L. Rohde, *Microwave Wireless Synthesizers*, John Wiley & Sons, Inc, 1997.

[5]U. L. Rohde, A. K. Poddar, and G. Boeck, *Modern Microwave Oscillators for Wireless Applications: Theory and Optimization*, John Wiley & Sons Inc, 2005.

[6]U. L. Rohde and A. K. Poddar, "Technological Scaling and Minimization of 1/f Noise in Coupled Mode Oscillator For Wireless Systems," *Microwave Journal*, June 2007.

[7]U. L. Rohde, A. K. Poddar, and R. Rebel, "Integrated Low Noise Microwave Wideband Push-Push VCO," *US Patent No.* 7,088189.

[8]U. L. Rohde and A. K. Poddar, "Noise Minimization Techniques for RF & MW Signal Sources (Oscillators/VCOs)," *Microwave Journal*, Aug. 2007.

[9]A. Grebennikov, "Noise Reduction in Transistor Oscillators," *High Frequency Electronics*, May 2005. *Writer's Handbook*. Mill Valley, CA: University Science, 1989.

[10]J. S. Schaffner, "Simultaneous Oscillations in Oscillators," *IRE Transactions on Circuit Theory*, Vol 1, no. 2, Jun 1954, pp 2-8. T. Endo and S. Mori, "Mode Analysis of a Multimode Ladder Oscillator," IEEE Transactions CAS-23, Feb 1976, pp 100-113.

Ulrich L. Rohde studied electrical engineering and radio communications at the universities of Munich and Darmstadt, Germany. He holds a PhD in electrical engineering (1978) and an honorary ScD (1979) in radio communications, a Dr-Ing (2004) from the University of Berlin, Germany in Oscillator Circuits and several honorary doctorates.

He is President of Communications Consulting Corporation; Chairman of Synergy Microwave Corp, Paterson, New Jersey; and a partner of Rohde & Schwarz, Munich, Germany. Previously, he was the President of Compact Software, Inc, Paterson, New Jersey; and Business Area Director for Radio Systems of RCA, Government Systems Division, Camden, New Jersey. He is a Professor of RF Microwave Circuit Design at Cottbus and has held Visiting Professorships at several universities in the United States and Europe.

Dr. Rohde holds several patents and has published more than 60 scientific papers in professional journals, contributed a chap-

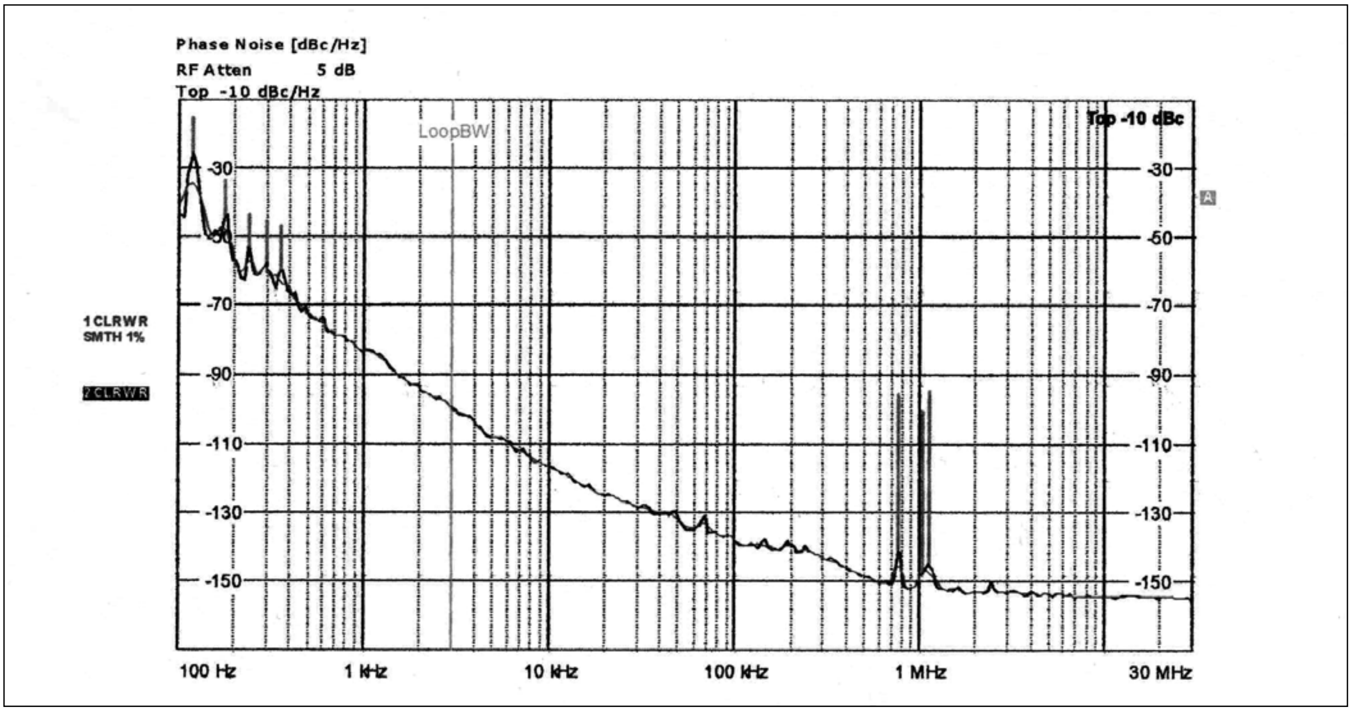

Figure 12 — Typical measured phase noise of a 1000 MHz 1960 vintage Rohde & Schwarz cavity stabilized tube oscillator. The two spurs shown are picked up from broadcasting stations.

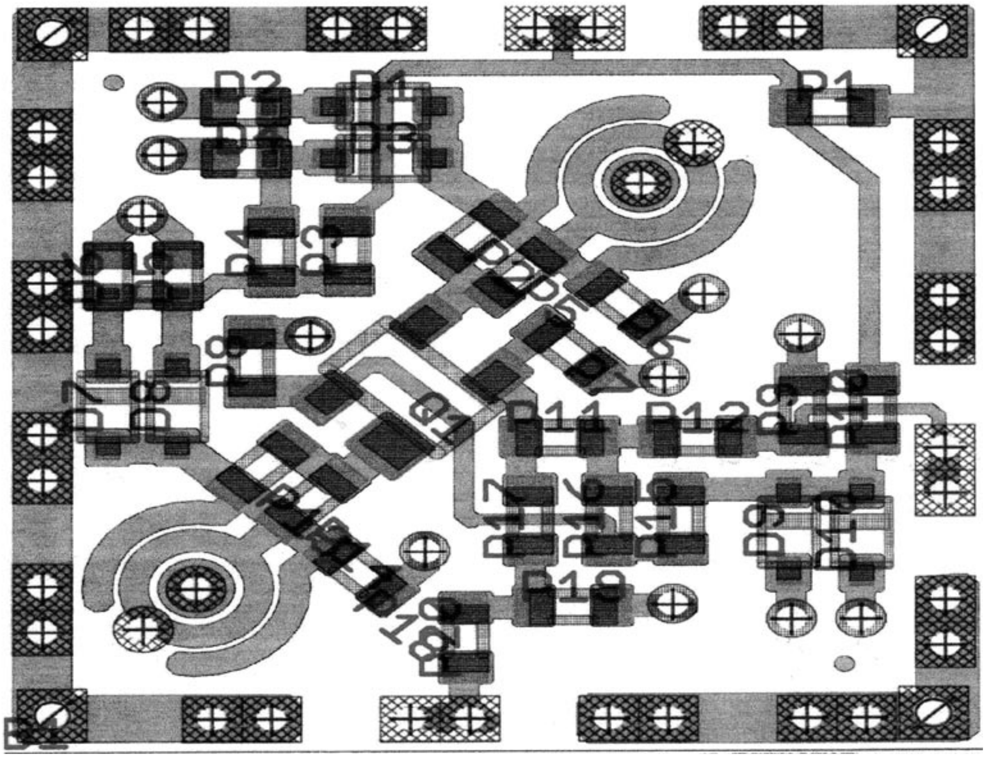

Figure13 — Typical layout of the wideband VCO using modern printed coupled resonator (Synergy Microwave Corp, USA).

ter entitled "Oscillators and Frequency Synthesizers" to The Handbook of Microwave and Optical Components*, 2nd Edition; contributed a chapter entitled "Frequency Synthesizers" to* The Wiley Encyclopedia of Telecommunications*, as well as six books:* Communications Receivers, *Third Edition;* RF/Microwave Circuit Design for Wireless Applications; Microwave and Wireless Synthesizers: Theory and Design; Microwave Circuit Design Using Linear and Nonlinear Techniques, *with co-authors George Vendelin and Anthony M. Pavio;* Communications Receivers: Principles and Design; and Digital PLL Frequency Synthesizers: Theory and Design.

Dr. Rohde is a member of the following: Fellow Member of the IEEE, Invited Panel Member for the FCC's Spectrum Policy Task Force on Issues Related to the Commission's Spectrum Policies, Eta Kappa Nu Honor Society, Executive Association of the Graduate School of Business-Columbia University, New York, the Armed Forces Communications & Electronics Association, fellow of the Radio Club of America, and former Chairman of the Electrical and Computer Engineering Advisory Board at New Jersey Institute of Technology. He holds German call signs, DJ2LR/DL1R since 1956, a Swiss call sign, HB9AWE and a US call sign, N1UL (formerly KA2WEU). QEX