A DIELECTRIC RESONATOR OSCILLATOR WITH 5 PPM LONG TERM FREQUENCY STABILITY AT 4 GHz

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Abstract

High Q, temperature stable dielectric resonators are excellent stabilizing elements for microwave transistor oscillators. A 4 GHz $Ba_2Ti_9O_{20}$ resonator integrated with a Si bipolar transistor in a compact oven has a frequency stability of 5 ppm/yr., 4° to 60°C (40 to 140°F). It is significantly simpler than alternative generators and has 10 to 20 dB lower FM noise. An 18 GHz generator is also described which uses a 4.5 GHz oscillator and a varactor quadrupler.

Summary

Dielectric resonators provide temperature stable, high Q resonant elements suitable for microwave integrated circuit applications.[1-4] A microwave oscillator using a $Ba_2Ti_9O_{20}$ ceramic resonator integrated into the feedback path of a transistor has important advantages. It is significantly simpler than any alternative microwave generator giving comparable stability and has much lower noise.

The use of a high Q resonator to generate power directly with a microwave transistor results in noise <0.4 Hz in a 1 kHz bandwidth at 1 MHz from the carrier. This result for a Si bipolar transistor is 10 to 20 dB lower than conventional microwave generators. In addition, the low temperature coefficient of the resonator combined with the use of a compact oven has resulted in a frequency stability <5 ppm/yr. from all effects over an ambient temperature range of 4 to 60°C. This stability, which meets the requirements of FM radio carrier supplies, is achieved with direct microwave generation without crystal control and without a phase locked loop.

For frequencies well above the 6 GHz band, the resonator Q and transistor gain become less favorable for direct generation. In these applications, best performance can be obtained by operating the oscillator at 6 GHz or lower and using a low order frequency multiplier. An 18 GHz generator is described which uses a 4.5 GHz stable oscillator and a varactor diode quadrupler.

Oscillator Design

The microwave oscillators use $Ba_2Ti_9O_{20}$ resonators possessing $\varepsilon = 40.0$ and $Q \geq 8000$ to 11,000 to 4 GHz. The quasi-free space temperature coefficient measured in waveguide is $\tau_f = +1.2$ ppm/°C + 0.02 ppm/°C^2 with a reference temperature of 25°C. The temperature coefficient of the brass or aluminum housing is used to compensate the linear term in τ_f. For operation at 4 GHz, the resonator diameter and height are 0.500 and 0.260 inches.

Although a number of oscillator configurations are possible, advantage was taken here of the small resonator size which permits the resonator to be simultaneously coupled to both the emitter and collector circuits of a bipolar transistor to form a feedback path. This circuit can be described by the Y-oscillator representation where the feedback admittance is formed by the combination of the resonator admittance, Y_R, and the emitter circuit admittance, Y_E. A linear analysis, using the transistor s-parameters, provides the initial values of Y_E and Y_R. The optimum values for Y_E, Y_R and Y_L are then determined under large signal conditions.

The oscillator module is shown in Figure 1. The emitter and collector circuits are positioned with the resonator located between them and supported on a quartz cylinder. This provides the coupling of both microstrip lines to the resonator $TE_{01\delta}$ mode and forms the feedback path. The common base transistor and the substrates are soldered to a carrier plate. Clearance is provided in the housing cover to avoid excessive resonator Q degradation. The housing cover contains a tuning screw for fine tuning of the oscillator frequency and also contains a chamber for the desiccant cartridge. A 20 dB directional coupler as shown in Figure 1 is included for aging tests only.

To obtain 5 ppm frequency stability, the total temperature effect is reduced to approximately $\pm$ 0.5 ppm over 4 to 60°C by locating the oscillator in an oven with a thermal gain of 50. Placing the oven control elements in the oven with the oscillator assures that ambient temperature effects are minimal. It is also important that an isolator be placed in the oven to minimize frequency pulling effects associated with the temperature dependence of the load. The actual load match at the oscillator is not critical, however, provided that it is stable after the frequency is set. Load match changes permissable are given in the following section. Integrated circuit construction made possible by the compact dielectric resonator assures that a very small and simple oven assembly can be used.

Humidity effects are relatively small for the ceramic resonator as only about 20 percent of the energy is stored in the external fields. To assure minimal frequency shift, humidity effects are controlled by enclosing a desiccant cartridge in the housing and using an O-ring seal. The absolute value of the humidity is unimportant provided that it is stable after the frequency is set. Permissable humidity changes are given in the following section.

Oscillator Performance

The oscillator module shown in Figure 1 was used for aging measurements. As mentioned earlier, a 20 dB directional coupler was used (instead of an integrated isolator). In addition, a discrete isolator with 25 dB isolation was connected outside the oscillator housing but inside the oven assembly to minimize load effects for these aging tests.

Frequency measurements were made with an electronic counter referenced to a quartz standard having an error less than 10^{-10}. Measurements on 15 oscillators over a period of 250 days indicate that the median frequency shift for the first year of operation is +3.3 ppm. Furthermore, all frequency shifts were in the same direction with the result that the frequency changes compensate each other in a typical system application. The aging data for two typical oscillators are given in Figure 2. Correlated ripples in the data are associated with temperature changes in a common environmental chamber used for these tests. On the basis of tests on 15 oscillators, we conclude that the frequency shift can be approximately extrapolated as a straight line on a log time plot. By offsetting the initial frequency 14 out of 15 oscillators meet a $\pm$ 4 ppm frequency stability for aging effects alone during the first year.

Table I shows the frequency shift contributions allocated for the various effects. Aging during the first year is the dominant effect followed by pulling. For the second and subsequent years aging should have an ever diminishing effect. Other contributions are virtually negligible.

The external Q for the test oscillators is typically 3000 to 4000. The measured noise Δf_{rms} is typically 0.35 Hz/$\sqrt{kHz}$ at 1 MHz from the carrier and 1.1 Hz/$\sqrt{kHz}$ at 10 MHz. The pushing was typically 5 ppm/volt. The output power (without the directional coupler) is typically 15 dBm.

For higher power applications the oscillator power is amplified with a transistor amplifier placed outside the oven assembly. This approach assures that the performance of the low power oscillator is not impaired.

An 18 GHz Generator

Figure 3 shows a microwave generator for the receiver of an 18 GHz digital radio system which combines a 4.5 GHz dielectric resonator oscillator with a varactor frequency quadrupler. The configuration shown was designed to mate with associated components in the receiver. Because of the relaxed frequency stability requirement, no oven is used in this application. The operating temperature range for the generator is -18 to 71°C (0 to 160°F).

The oscillator module is shown in Figure 4. A "folded" type structure is used, where the emitter and collector circuit substrates are located on opposite sides of a carrier plate. This configuration can be visualized as a planar circuit which is folded at opposite sides of the transistor. The "folded" circuit possesses several features: (1) the oscillator is small; (2) the emitter and collector circuit substrates are supported on opposite faces of a common carrier plate; (3) Q degradation due to the proximity of the ground plane is minimal; (4) spurious resonator coupling to the circuit is reduced. The frequency is determined to within a few MHz by the dielectric resonator dimensions and is trimmed to the desired frequency with the tuning screw.

The varactor quadrupler and 4.5 GHz isolator are integrated on a teflon-fiberglass circuit board as shown in Figure 5. Stripline is used for the quadrupler and microstrip for the isolator. The quadrupler uses a varactor diode which is mounted on the stripline probe projecting through the sidewall of the output WR-42 waveguide. Adjustment of the bias voltage is used to resonate the diode at $2f_o$. The second harmonic idler circuit resonance is completed by the quarter wavelength probe which also prevents $2f_o$ excitation of the input line. The diode location determines the fourth harmonic coupling to the waveguide. The two $4f_o$ stubs prevent fourth harmonic leakage into the input line and complete the resonance of the diode.

The 18 GHz output isolator is an internally terminated waveguide circulator built in WR-51 waveguide.

The 4.5 GHz output power of the oscillator can be varied over the range of 10 to 15 dBm by setting the transistor bias. The oscillator efficiency ranges between 11 and 17% including the stabilizing resonator losses. The conversion loss in the quadrupler is 6 to 7 dB (≈20 to 25% efficiency). The resulting adjustable output power is 3 to 8 dBm at 18 GHz.

The performance of a typical generator at 18 GHz is presented in Figure 6. Power curves for three values of transistor bias are shown. Over the -18 to +71°C (0 to 160°F) range the power is flat to within $\pm$ 0.4 dB and the frequency stability is $\pm$ 20 ppm. With 25°C taken as the reference point, the linear and quadratic temperature coefficients are -.12 ppm/°C and +0.02 ppm/°C^2 respectively.

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Table I

Frequency Stability Allocation For 4 GHz Bipolar Oscillator With $Q_{ex} \sim 4000$

Effect	Tolerance	Control	Sensitivity	Stability
Pushing	$\pm$0.1 Volt	Power Supply Stabilization	5 PPM/Volt	$\pm$0.5 PPM
Pulling	$P_{inc}/P_{out} = -40$dB	Isolation and Load Match	$\frac{\Delta f}{f} = \frac{1}{Q_{ex}}\left(\frac{Pinc}{Pout}\right)^{1/2}$	$\pm$2.5 PPM
Humidity	$\Delta p < .2$ mmHg	O-Ring Seal with Desiccant	0.8 PPM/mmHg @60°C	$\pm$ .1 PPM
Temp.	Thermal Gain ⩾50 4-60°C	Oven	<0.7 PPM/°C @65°C	$\pm$0.5 PPM
Aging (1st Year)	-	Transistor Stability		$\pm$4.3 PPM
RMS Total, All Effects over 1 Year				$\pm$5 PPM

Where Q_{ex} is the external Q for the oscillator.
P_{inc} is the incremental change in reflected power at the oscillator port.
Δp is the incremental change in partial pressure of H_2O vapor.

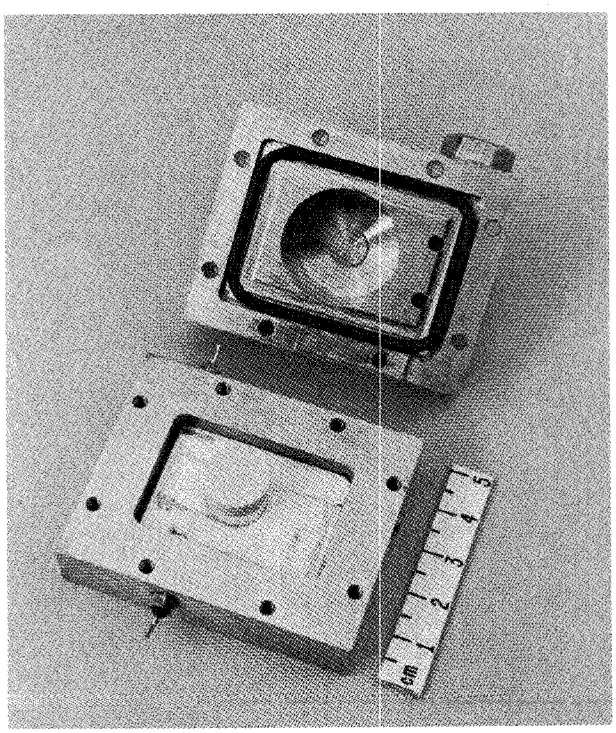

Fig. 1-4 GHz dielectric resonator stabilized oscillator.

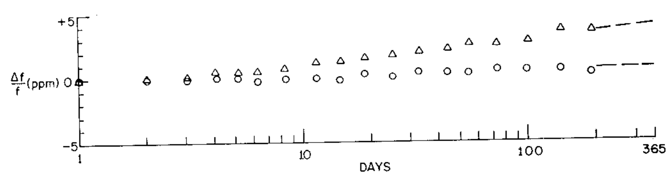

Fig. 2-Aging of two typical 4 GHz oscillators.

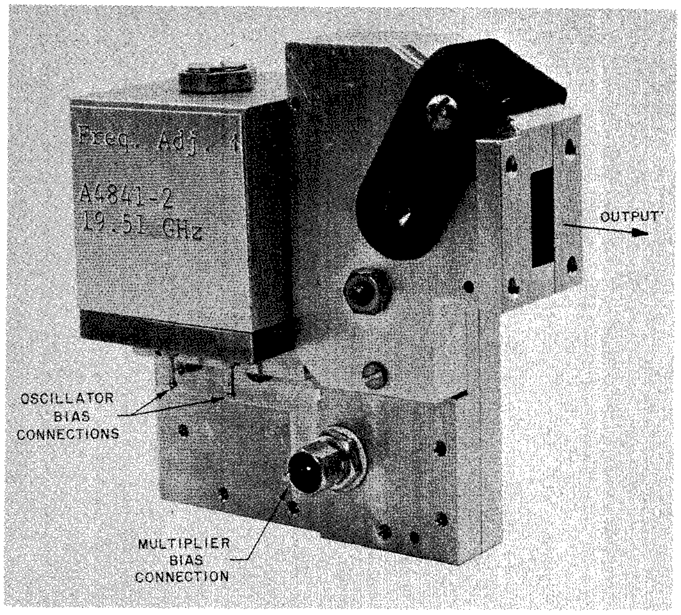

Fig. 3-18 GHz generator using a 4.5 GHz dielectric resonator stabilized oscillator and a varactor frequency quadrupler. The generator has integrated isolators at 4.5 GHz and 18 GHz to minimize pulling effects.

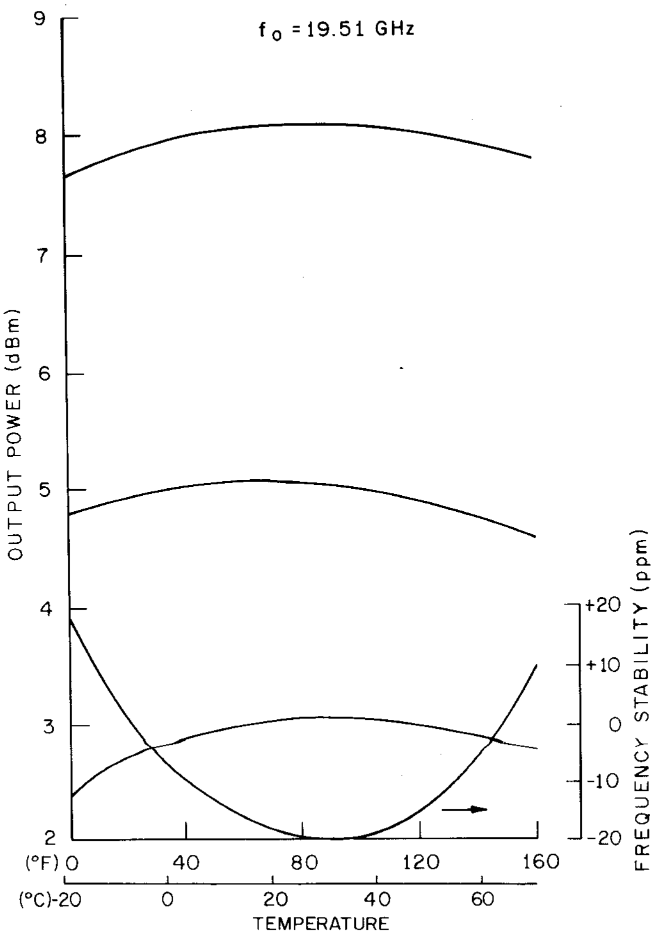

Fig. 6-Characteristic for a typical 18 GHz generator. Power curves for three values of transistor bias are shown.

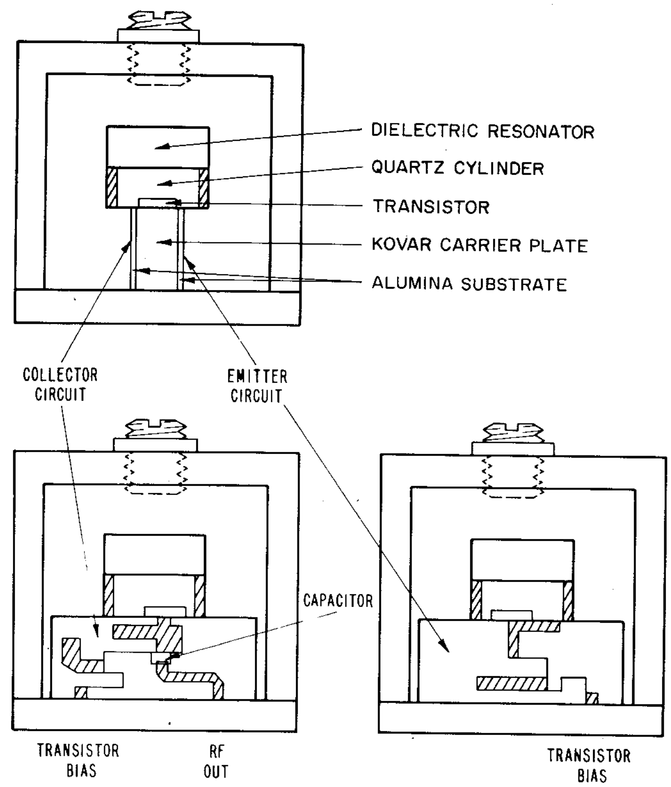

Fig. 4-4.5 GHz folded oscillator module used in the 18 GHz generator.

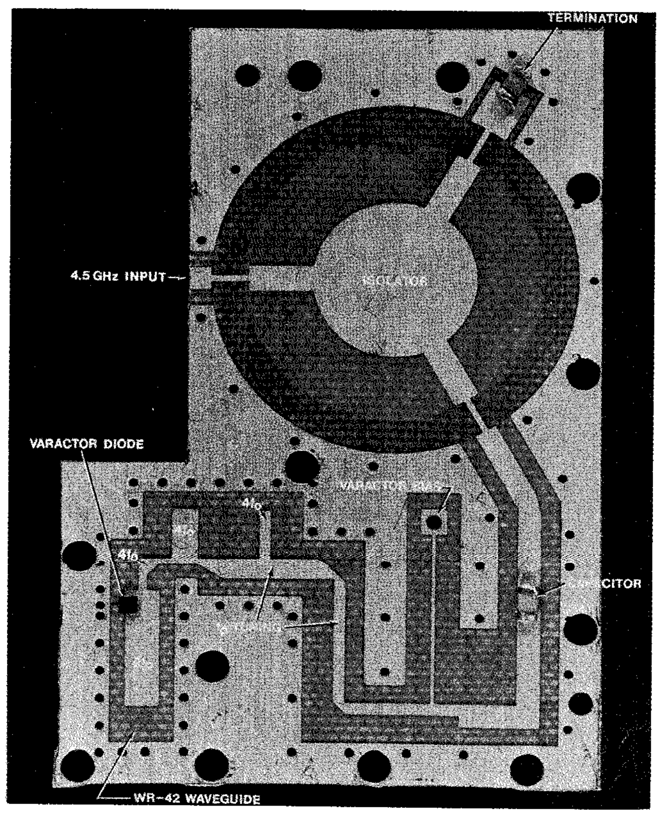

Fig. 5-4.5 GHz isolator and quadrupler circuit board.