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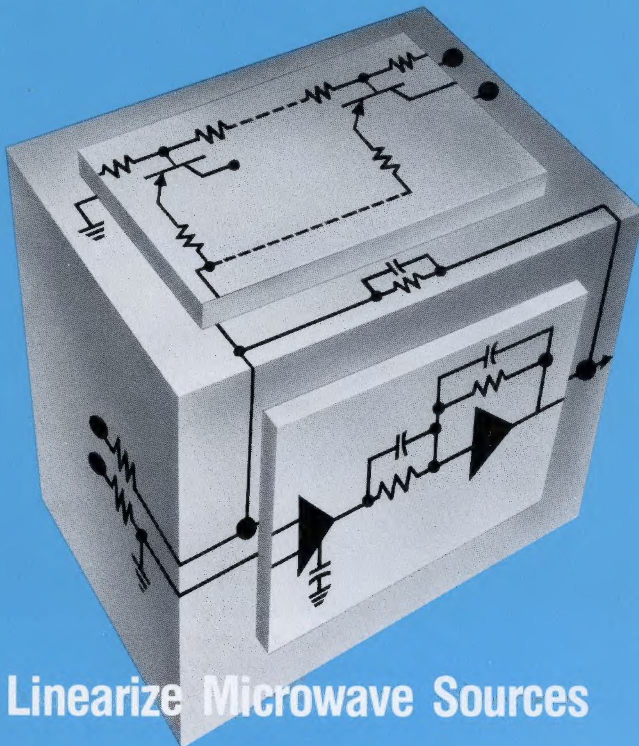
WATKINS-JOHNSON COMPANY Tech-notes

Linear VCOs



Linearize Microwave Sources

The high power output, large input bandwidth and very fast tuning speed characteristics of the varactor-tuned voltage controlled oscillator (VCO) have improved the performance of many EW systems which require a microwave signal source. As a microwave signal source, it may be used as a local oscillator (LO) or transmitter in radar applications, as a noise source for active jammers, and as a LO for superheterodyne receivers. The development of the linearizer which transforms the VCO's nonlinear tuning characteristic into a linear function is one more step toward improved system performance by reducing the complexity of components interfaced to the VCO.

In EW receiver applications, the linearizer/VCO combination now permits direct computer commands through a linear digital-to-analog converter to tune to a desired RF frequency without complex and costly nonlinear conversion circuitry. For transmitters required to modulate at a number of different RF frequencies in either a time-shared or frequency multiplex mode, the linearizer/VCO combination allows transmitters to advance from wideband, wide frequency deviation modulation microwave noise sources to smart jammers—frequency hopping over many bands to cover multiple threats.

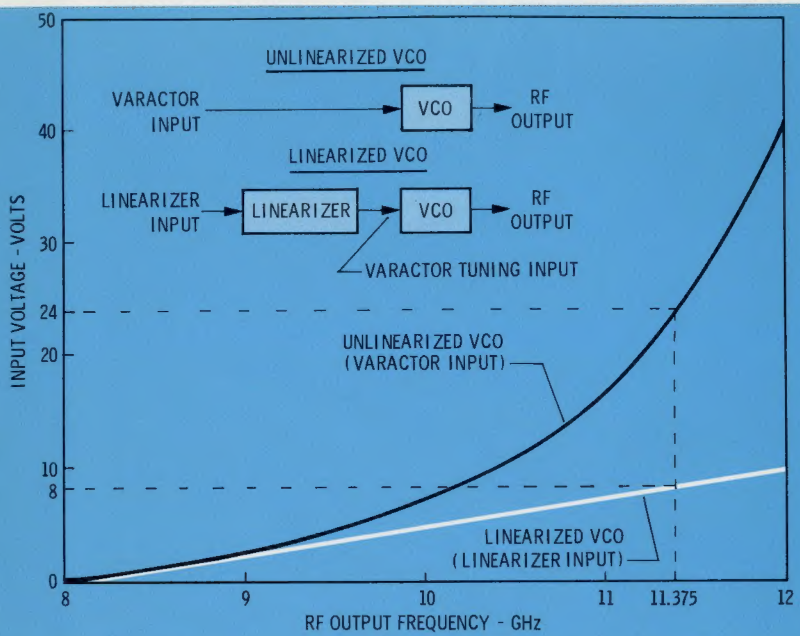


Fig. 1. Linearizer transformation of an 8-12 GHz VCO's exponential tuning characteristic to a constant voltage range linear tuning characteristic.

Nonlinear to Linear Tuning

Varactor-tuned VCOs generally have a nonlinear voltage versus RF frequency tuning characteristic, as shown in Figure 1 by the example 8-12 GHz unlinearized VCO. The unlinearized RF output frequency increases monotonically with varactor input voltage which ranges from typically .3 to 40 volts. Only one value of frequency exists for each value of tuning input across the entire frequency range.

However, the addition of a linearizer to the VCO input transforms the high-voltage nonlinear varactor tuning characteristic into a lower voltage linear function at the linearizer input. Therefore, a constant input voltage range (typically 0 to 10 volts) may be applied to the linearizer to achieve

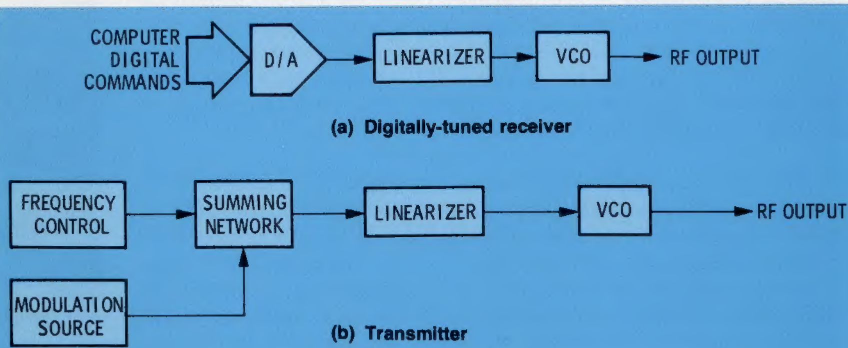


Fig. 2. Frequency agile local oscillator and fast modulated noise source applications of the linearized VCO.

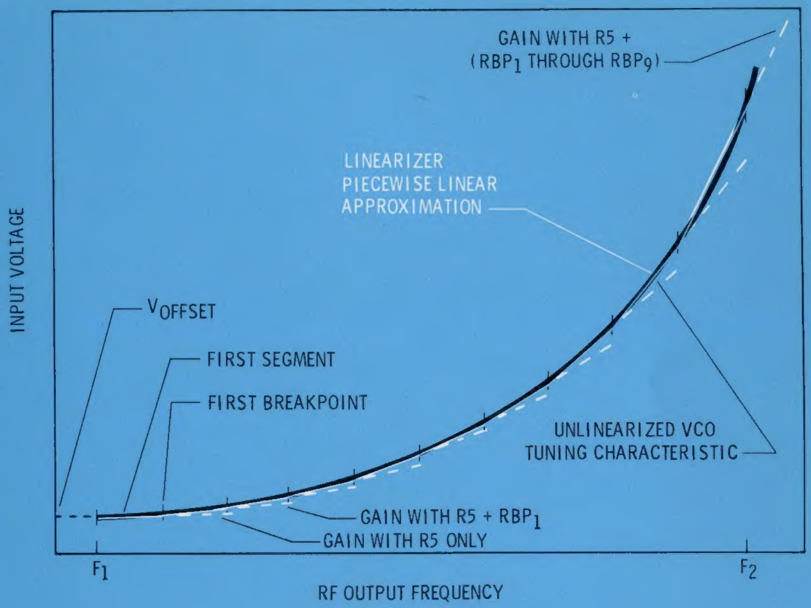


Fig. 3. Piecewise linear approximation of the VCO's tuning characteristic.

the same RF frequency range. In addition, the linearizer stabilizes the VCO's varactor input, which exhibits a wide variation in input impedance, by providing a fixed input impedance of 1 to 10 kilohms for VCO input bandwidths up to 1 MHz.

Linearized VCO Receiver and Transmitter Applications

The linearizer/VCO combination is most widely used as either a frequency agile local oscillator in receiver applications or fast modulated noise source in transmitter applications. An example of the linearized VCO used as a local oscillator in a digitally-controlled receiver is shown in Figure 2a. The linearizer permits direct digital commands to tune the VCO to the desired RF frequency without a nonlinear function within the system's digital-to-analog converter. In this application, the rate at which the receiver tunes to the commanded frequency (referred to as tuning speed) is determined by the VCO and its driving circuitry.

In EW transmitter applications, noise is generated by frequency modulating the VCO as shown by the linearized VCO transmitter in Figure 2b. Here the VCO provides the transmitter with the capability of being modulated over broad (1 GHz) or narrow (10 MHz) bandwidths at fast tuning rates. Since the linearizer transforms the VCO's tuning characteristic into a lower voltage linear characteristic, the resulting RF output modulation density or power density (watts/Hz) is essentially constant over the full output frequency range.

Linearizer Circuit—A Piecewise Linear Approximation To The VCO Tuning Characteristic

In order to match the VCO's unlinearized tuning characteristic, the linearizer makes a piecewise linear approximation to the tuning characteristic as shown in Figure 3. The approximation curve is often divided into equal frequency divisions as

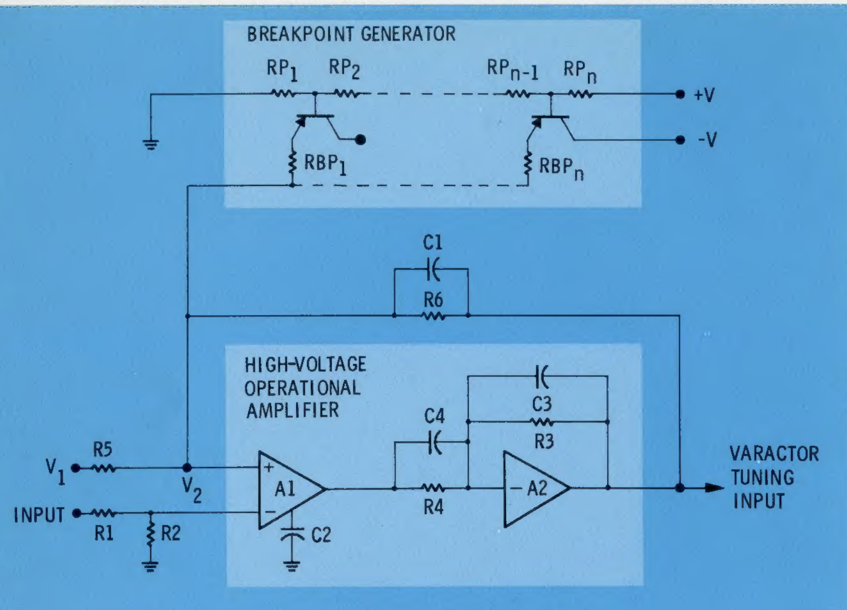


Fig. 4. Linearizer circuit schematic.

illustrated by the ten equal straight line frequency segments. The actual tuning curve of the linearized VCO will fall within some small deviation (nonlinearity) about a straight line drawn between two points on the linearized VCO tuning characteristic. By increasing the number of frequency segments, the nonlinearity may be significantly reduced.

The linearizer circuit, which approximates the varactor-tuned VCO tuning characteristic by small, straight line segments, is shown in Figure 4. In this circuit, a high-voltage operational amplifier is used to accommodate the voltage requirements of the VCO, and a breakpont generator is used to change the gain of the operational amplifier at successive predetermined voltages or "breakpoints." In effect, the breakpoint generator adjusts the operational amplifier gain for the closest possible match to the VCO's tuning characteristic.

Since most VCO tuning characteristics are offset from zero volts at the low-end frequency, F_1, the linearizer must also provide this voltage offset at the VCO input when the input voltage to the linearizer is zero. In the circuit of Figure 4, this offset is obtained from the voltage V_1 applied to the inverting amplifier input through resistor R5, and is given by the equation:

$$V_{offset} = -V_1 \times \frac{R_6}{R_5}.$$

In order to match the slope of the VCO's tuning characteristic, the operational amplifier gain is adjusted over successive frequency segments. During the first frequency segment, the operational amplifier gain is given by the equation:

$$G = \left(\frac{R_2}{R_1 + R_2}\right)\left(1 + \frac{R_6}{R_5}\right).$$

where R_5 is the same resistance value used to establish the voltage offset.

To match the VCO's tuning characteristic for the second and successive frequency segments, the gain of the operational amplifier is increased at each breakpoint by decreasing the inverting input resistance to the operational amplifier. As the input voltage is increased from zero volts, the voltage at V_2 is also increased. Voltages at the bases of the breakpoint transistors are adjusted so these transistors turn on within the range of V_2. Therefore, as the tuning voltage increases, successive breakpoint transistors turn on and shunt R_5 with breakpoint resistors RBP_1–RBP_n. As a result, the gain of the operational amplifier is increased in proportion to the ratio $-R_6/R'_5$, where R'_5 is an equivalent input resistance. In effect, the inverting input resistance R'_5 to the operational amplifier is decreased by shunting R_5 with an additional breakpoint resistor for each additional frequency segment. All the breakpoint resistors shunt R_5 at high-end frequency, F_2.

The breakpoint resistors, RBP_1—RBP_n, are selected to match the tuning characteristic of each varactor-tuned VCO driven by the linearizer. Resistors, RP_1–RP_n, position the points along the tuning characteristic at which the breakpoint transistors turn on.

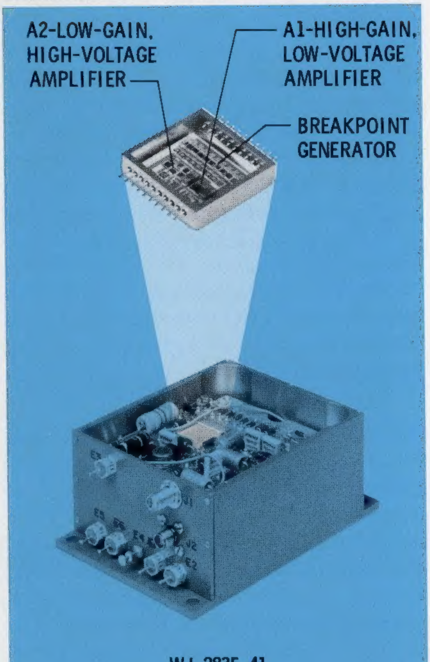


Fig. 5. A ⅝ inch square hybrid linearizer mounted in an 8-12 GHz varactor-tuned VCO.

Since the VCO may require a varactor tuning input voltage as large as 60 volts to tune across an octave frequency range, the linearizer operational amplifier must be capable of supplying this voltage as an output. In order to achieve this high voltage requirement and a video bandwidth on the order of 1 MHz, and to minimize settling time and post tuning drift, the operational amplifier contains a low-voltage, high-gain stage (A1) followed by a high-voltage, low-gain stage (A2).

The high-voltage stage has an open-loop gain on the order of 400 and a closed-loop gain of 10. Its modulation bandwidth exceeds 1 MHz. The low-voltage stage has an open-loop gain of 10,000, and its modulation bandwidth in this application is in excess of 2 MHz. The combined amplifier has an open-loop gain greater than 100,000, which achieves the desired stability, and a modulation bandwidth greater than 1 MHz for a 50 volt output.

Hybrid Linearizer/VCO Components

To accommodate the requirements for small size in EW applications, and to effectively heat sink and temperature stabilize the linearizer circuit, a hybrid linearizer design is mounted within the varactor-tuned oscillator unit as shown in Figure 5. The hybrid contains the high-gain and high-voltage stages of the operational amplifier, and breakpoint generator.

The hybrid circuit is fabricated on a 0.025 inch alumina substrate and mounted in a 20 lead flat pack. Voltage polarity in or out of the hybrid can be of two versions—one having a positive input and output, and the other having a negative input and output. Since the common interface voltage range is 0 to +10 volts, and optimum varactor-tuned VCO performance is achieved with a negative varactor input voltage, an input inverter amplifier is incorporated into the PC board to drive a negative output linearizer.

Linearizer Effect on VCO Performance

In addition to the linerizer's effect on the VCO's tuning characteristic, it also affects the more subtle VCO characteristics such as settling time, post tuning drift and modulation sensitivity variation. For digitally-tuned receiver applications, higher tuning speed permits a faster settling time or time to attain a desired frequency after a step change in input voltage. Since the VCO is capable of a settling time within tens of nanoseconds, the linearizer and its driving circuitry are the primary limitations on settling time. Post tuning drift may also result from either a drift in the linearizer's output voltage or the VCO's resonant frequency when the input voltage is constant. In transmitters, the linearized VCO's input bandwidth determines the speed at which the transmitter can be modulated. Since the VCO's modulation bandwidth is relatively high, the limitation on this parameter is also within the modulation circuitry of the linearizer and its driving circuitry.

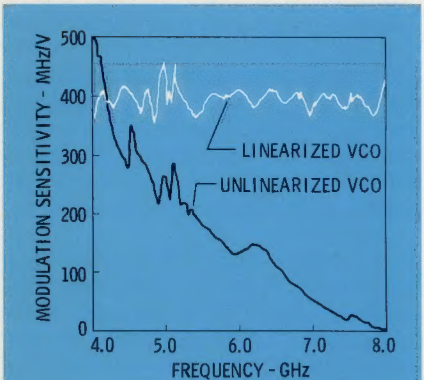


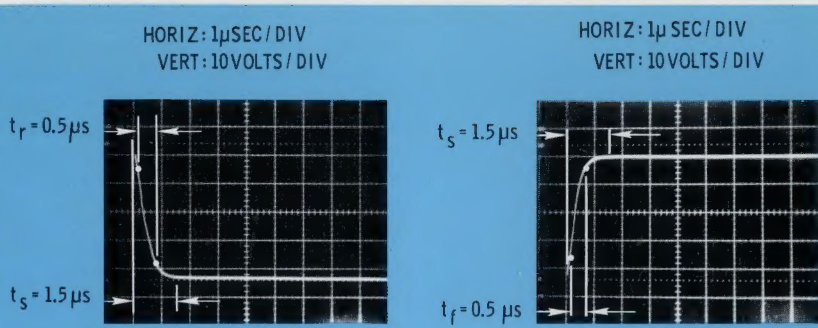
Fig. 6. Modulation Sensitivity Variation of a 4-8 GHz unlinearized and linearized VCO.

In either application, the tuning smoothness (fine grain variation in modulation sensitivity) is important. For transmitters modulated over a certain spectrum, smoothness of the tuning characteristic determines how constant the power density will be over a given band. In digitally-tuned receivers, the variation in the frequency step size for a given input voltage step will be governed by the modulation sensitivity variation. Fine grain variations in modulation sensitivity are present in the VCO itself; however, the linearizer may cause additional fine grain variations, since it makes a piecewise linear approximation to the VCO tuning characteristic.

Modulation Sensitivity Variation and Nonlinearity

The overall variation in modulation sensitivity (tuning slope) of a VCO is determined by the varactor capacitance-voltage characteristic and its relationship to the RF impedance of the VCO's transistor or bulk-effect diode. It may be as high as 20:1 for an octave bandwidth unit. In addition to the overall change in modulation sensitivity, the VCO tuning curve exhibits fine grain variations due to the effect of the load impedance on the oscillator's resonant circuit and the presence of small parasitic resonances in the RF section. The modulation sensitivity characteristic of a 4-8 GHz unlinearized VCO showing the overall and fine grain structure is shown in Figure 6.

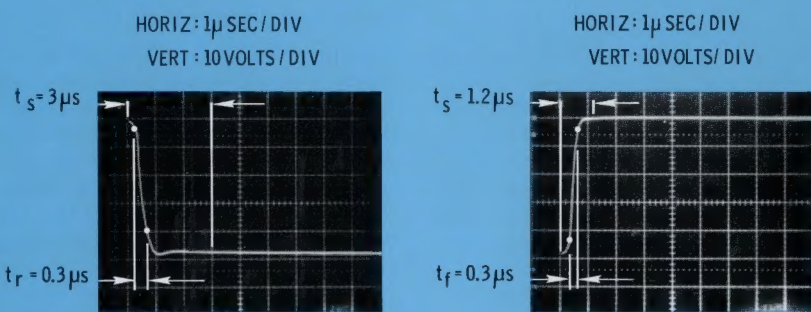
Because of the piecewise linear approximation to the VCO's tuning characteristic and the VCO's fine grain variations, the linearized VCO exhibits a certain degree of nonlinearity, that is, deviation from an ideal tuning characteristic expressed as a percentage of absolute frequency. For octave bandwidth units, a nonlinearity of $\pm 0.5\%$ is readily achieved. For narrowband VCOs (10-15% bandwidth) the nonlinearity may be improved to $\pm 0.1\%$.



(a) Rise Time (t_r) and Settling Time (t_s) for a step up in frequency.

(b) Fall Time (t_f) and Settling Time (t_s) for a step down in frequency.

Fig. 7. Step responses of the hybrid linearizer optimized for settling time.



(a) Rise Time (t_r) and Settling Time (t_s) for a step up in frequency.

(b) Fall time (t_f) and Settling Time (t_s) for a step down in frequency.

Fig. 8. Step responses of the hybrid linearizer optimized for bandwidth.

The overall variation in modulation sensitivity is eliminated by the linearizer. However, fine grain variations in the modulation sensitivity will be increased because of the linearizer's piecewise approximation to the VCO's exponential tuning characteristic as shown in Figure 6. Increasing the number of breakpoints, or by carefully selecting the breakpoint positions, this effect as well as the nonlinearity may be further reduced.

Settling Time and Modulation Bandwidth

The requirements placed upon a linearized VCO for receiver and transmitter applications are not necessarily compatible. A linearized VCO optimized for maximum modulation bandwidth will not necessarily settle as fast as when the same unit is optimized for minimum settling time.

A linearizer may be aligned for either minimum settling time or maximum modulation bandwidth by using different compensation techniques. When the linearizer is optimized for minimum settling time as shown in Figure 7, the output RF frequency stabilizes to 1.0% of the final frequency within 1.5 microseconds after a full band step change in input voltage. The 3 db modulation bandwidth (full band) is 575 KHz and falls off at 12 dB/octave since the gain of each operational amplifier stage, A1 and A2, falls off at 6 dB/octave. In order to prevent oscillation of the operational amplifier, a "zero" is introduced into the linearizer circuit (capacitance

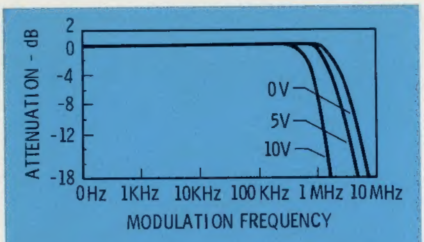


Fig. 9. Hybrid linearizer small signal bandwidth for input voltages of 0, 5 and 10 volts.

C_4 in Figure 4) which reduces the operational amplifier gain to 6 dB/octave before going through unity gain.

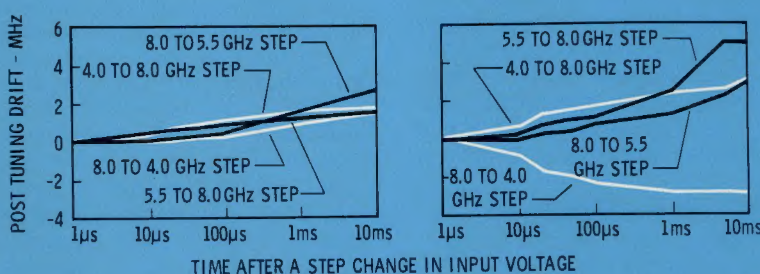
When optimized for modulation bandwidth, the same linearizer achieves a 1.0 MHz bandwidth (full band) which also falls off at 12 dB/octave. The rise and fall times are faster, as shown in Figure 8; however, the 1.0% settling time is increased to 3 microseconds due to pulse overshoot. Optimum modulation bandwidth is achieved by decreasing the capacitance of C_1–C_3 in the linearizer circuit of Figure 4.

In many applications a minimum small signal bandwidth is required. However, for a linearizer with breakpoints this parameter is not constant across the VCO's operating frequency range. As a result of the increase in operational amplifier gain required to match the VCO tuning characteristic, the small signal bandwidth decreases as the input voltage is increased for a fixed set of compensation capacitors. This is illustrated in Figure 9, where the bandwidth decreases from 2.1 MHz for an input of 0 volts to 750 KHz for an input of 10 volts.

The transient and frequency responses of the linearizer/VCO combination are essentially the same as those for the hybrid linearizer, since the bandwidth of the VCO is at least an order of magnitude greater in this example.

Post Tuning Drift (PTD)

Once the linearized VCO settles to a given frequency, thermal time constants of critical components cause a shift in output frquency as a function of time after a step change in input voltage, referred to as short-term post tuning drift. In the linearizer this may be caused by drifts in the operational amplifier itself. However, with an open-loop gain greater than 100,000 and use of resistors having a low temperature coefficient, this is a relatively small factor compared to the shift in breakpoint position due to changes in the base to emitter voltage (V_{BE}) of the breakpoint transistors. When the input is changed from 0 to 10 volts each breakpoint transistor goes from cutoff to an "on" condition.



(a) Unlinearized VCO

(b) Linearized VCO

Fig. 10. Post Tuning Drift characteristics of a 4-8 GHz VCO.

Heat generated in the transistor junctions causes the base to emitter voltage to decrease at a rate determined by the thermal impedance of the transistors and packaging. The thermal time constant of these devices is typically less than 1 millisecond. The decrease in V_{BE} causes the point at which the transistors turn on to shift, resulting in a change in the linearizer's output voltage and, therefore, the VCO's output frequency.

Similar effects occur in the VCO itself in which case both the varactor and active device (transistor or bulk-effect diode) exhibit a change in RF impedance after an input voltage step. The RF impedance change results from a change in junction temperature since the efficiencies of the active devices are frequency sensitive. The thermal time constant associated with the devices in the VCO may be as long as 1 millisecond.

A comparison of the short-term PTD of a 4-8 GHz VCO with and without linearizer is shown in Figure 10. The PTD is increased from a maximum of 2.6 MHz to 5.1 MHz by the addition of the linearizer.

VCO Noise

Noise associated with the VCO output signal is measured in terms of its residual FM. It is expressed as the peak-to-peak deviation at the top of the carrier, or as the sideband level a certain distance from the center of the carrier. The peak-to-peak residual FM of a 4-8 GHz VCO is typically 15 KHz. The addition of a linearizer causes this to increase to approximately 25 KHz. The sideband level also increases with the linearizer as shown in Figure 11. The noise 1 MHz from the carrier in a 10 KHz bandwidth typically increases from −60 dB to −36 dB. This noise is generated in the linearizer circuit and cannot be reduced by the operational amplifier's open-loop gain because it is relatively low compared to the closed-loop gain at that frequency.

One method to reduce the sideband noise is to place a filter between the linearizer and VCO. For example, a 10 KHz bandwidth filter placed after the linearizer will reduce the VCO's output sideband noise essentially to the same level as for the VCO itself, however, this also limits the linearized VCO modulation bandwidth.

Faster Linearizers Yield Improved System Performance

In order to reduce a receiver's acquisition time or to increase the number of threats covered by a transmitter in a certain time frame, the tuning speed and modulation bandwidth of the linearized VCO are increased to achieve faster system performance.

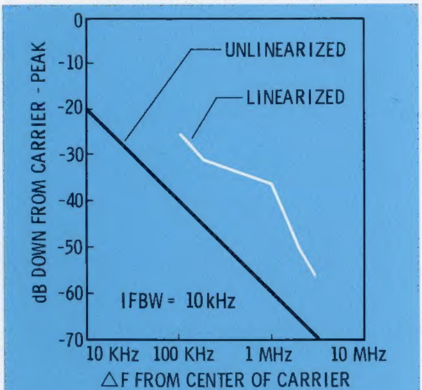


Fig. 11. Noise characteristics of a 4-8 GHz unlinearized and linearized VCO.

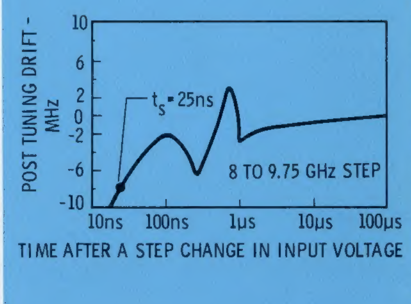


Fig. 12. Post Tuning Drift characteristic and fast settling time of an 8-10 GHz linearized VCO.

Linearized octave bandwidth units are being developed which are capable of tuning speeds greater than 40 GHz/microsecond and modulation bandwidths in excess of 10 MHz. Narrow bandwidth units (25-35%) are becoming available which exhibit 0.1% settling times less than 25 nanoseconds and modulation bandwidths exceeding 100 MHz. The post tuning drift of an 8-10 GHz linearized VCO is less than 8 MHz measured in the time range from 25 nanoseconds to 100 microseconds, and is shown in Figure 12. At these speeds the interface between the linearizer and VCO becomes critical since the modulation bandwidth of each device is comparable. This performance can only be achieved by integrating the linearizer and VCO to minimize lead lengths and parasitics.

Summary

In most VCO applications, a transformation of the exponential tuning characteristic to a linear function is required for interface with the rest of the system. A linearizer performs this function and makes the device interchangeable with only minimal alignment if the linearizer is integrated with the VCO.

To reduce VCO size, minimize PTD, and simplify assembly, a hybrid version of the linearizer circuit was developed. This unit is capable of a 1 MHz modulation bandwidth and settling times less than a few microseconds.

Extension of linearizer technology has yielded very fast settling time VCOs, however, only over limited frequency ranges. It is anticipated that this technology will be expanded to include octave bandwidth units in the near future.

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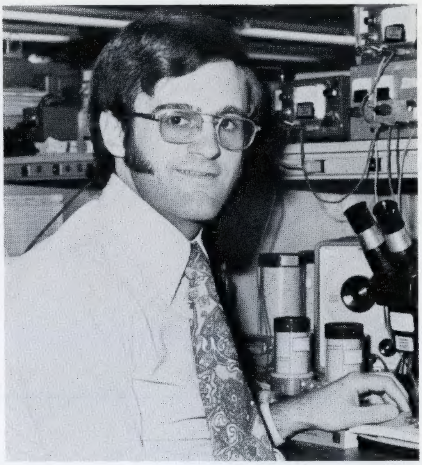

Mr. Buswell is currently Head, Design Engineering Section, Solid State Department at W-J's Stewart Division. He is also the author of the article "VCOs in Modern ECM Systems" which appeared in the November/December, 1974 issue of Tech-notes. His advances in linearizer circuitry have contributed to the successful development of 1 MHz octave bandwidth linearized VCOs and the 100 MHz sub-octave bandwidth linearized VCO described in this article. Future activity in his section includes the development of a 10 MHz octave bandwidth linearized VCO.

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