OSCILLATOR DESIGN TECHNIQUES ALLOW HIGH FREQUENCY APPLICATIONS OF INVERTED MESA RESONATORS

By   Kurt Wessendorf
Sandia National Laboratories
Albuquerque, New Mexico

Tom Payne
President
Avance Technology
Cedar City, Utah

By using inverted-mesa techniques to selectively thin the resonator, the practical upper frequency range of bulk wave crystal oscillators has risen dramatically over the past several years. A new technology called Tab-mesa Technology (TmT) has paved the way for new design approaches in telecommunications applications including small, portable high-frequency equipment such as pagers, cellular telephones, keyless entry and other wireless communications systems. Many designers have shied away from these new devices because of the lack of standardized design practices. Fortunately, as this article will demonstrate, many classic bulk wave designs can be adapted to high frequency operation when the new crystals are used in the fundamental mode.

Most existing high-frequency equipment is built around surface acoustic wave (SAW) resonators. The SAW resonator consists of two transducers with arrays of fine metal electrodes deposited on a highly polished piezoelectric substrate such as quartz or lithium niobate. The arrays are comprised of electrodes that alternate polarities. When an RF signal voltage of the proper frequency is applied across them, the surface of the crystal expands and contracts, generating a displacement wave on the surface of the crystal.

TmT Bulk Acoustic Wave Resonator Model

Bulk acoustic wave (BAW) resonators operate on entirely different principles. The displacement wave produces a resonating vibration which travels through the crystal. The crystallographic orientation used in manufacturing BAW devices is crucial to their performance characteristics. For applications in the Megahertz range, the AT-cut is the most common orientation because of its relatively low temperature coefficients. Figure 1 is the electrical equivalent model of the AT-Cut resonator. This model shows only the fundamental and the first two overtones of the resonator. Also, not shown in this model, are the spurious modes that can exist. These modes are process driven and can be kept relatively lossy in a well designed and fabricated resonator. C_0 is the static capacitance of the resonator which is in parallel with the motional arms (C_m, L_m and R_m) which are a function of the piezoelectric properties of the quartz.
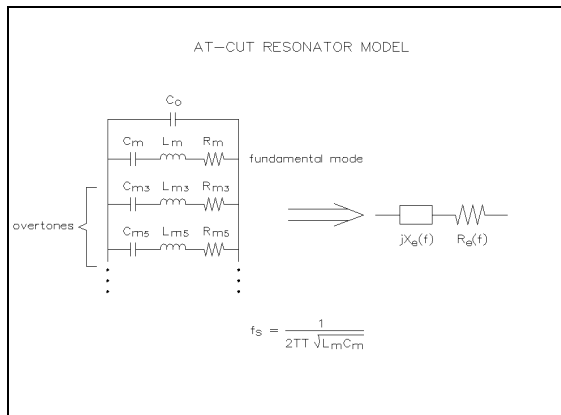
Figure 1. AT-Cut Resonator Model

Figure 2 graphically illustrates the resonator's reactive impedance, X_e, versus frequency [1]. (This graph is not drawn to scale).
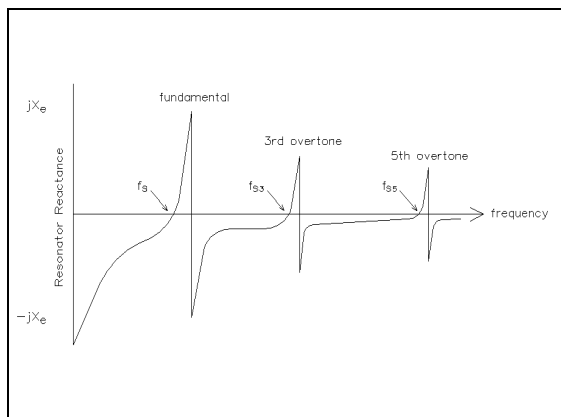

Figure 2. Resonator Reactive Impedance vs. Frequency

Typically an oscillator will be using the resonator in the inductive region, or as a resistive element very near f_s. The fundamental resonant frequency of the AT-cut crystals generally specified today is 1-30 MHz. In AT-cut crystals, the thickness of the crystal wafer determines the frequency–the thinner the wafer the higher the frequency. Unfortunately, thin wafers are very fragile and difficult to handle without breakage, limiting the fundamental frequency of these devices. The AT-cut resonator can also be operated on odd mechanical overtones of the fundamental frequency, generally the third and fifth. These overtones are higher Q than the fundamental and demonstrate superior aging characteristics.

Using inverted mesa technology, crystals can now be produced in the fundamental frequency range of 40 MHz to 200 MHz with overtones to 600 MHz. The inverted mesa process uses chemical etching to reduce the thickness of the quartz in the center region of the blank, leaving a thicker outer ring for added crystal strength. Inverted mesa technology permits higher frequencies than were previously possible with flat AT quartz crystals. The tiny geometry of these resonators also minimizes the static capacitance (C_0) of the devices which allows for higher loaded Qs at high frequencies. However, the use of inverted mesa crystals has been limited by their high cost and the difficulties associated with volume production.

TmT involves batch processing crystals using photolithographic techniques similar to those used in semiconductor processing. In a process developed by Avance Technology, a SaRonix company located in Cedar City, Utah, one by two inch quartz wafers are lapped and polished to approximately 3 mil thickness. 130 individual resonators approximately 50 by 170 mil in size are formed photolithographically on each wafer with the resonating region etched down to 0.5 mil or less depending on the desired frequency. Calibration to the exact frequency is accomplished by evaporating a thin gold layer onto the resonating region. The individual resonators are attached at their supporting 3 mil end onto headers using conductive epoxy and then hermetically sealed into a cylindrical metal or rectangular ceramic enclosure.

This manufacturing technology makes volume production of consistent quality, high frequency crystals possible. The thin resonating region of TmT crystals is cantilevered from a thicker base, enabling a much smaller crystal design. The inherent small size of these unique crystals makes it possible to package the miniature devices in 2 mm by 5 mm tubular casings similar to those used in the watch crystal industry. When mounted in a conventional hybrid oscillator circuit, the TmT crystal is hermetically sealed in its own enclosure. This eliminates the most common sources of crystal failure in hybrid

oscillators–blank fractures and contamination. The low mass of quartz blanks mounted in small, sealed metal or ceramic packages results in rugged components that are much less susceptible to shock, vibration and handling damage. These devices provide an attractive alternative to SAW devices in many applications.

High-Frequency Oscillator Designs

Traditional 2-port SAW oscillator designs are based upon a 50Ω gain block, Figure 3. The power efficiency and minimum operating power of this type of design is limited by the gain block (amplifier) and the low impedance splitter. Since the gain blocks typically use shunt feedback for matching, relatively large bias currents (tens of milliamps) are required to achieve the gain required to drive the low impedance SAW and splitter. In many designs milliamp or sub-milliamp currents may be desired to meet a low overall current (thus power) budget of a system.
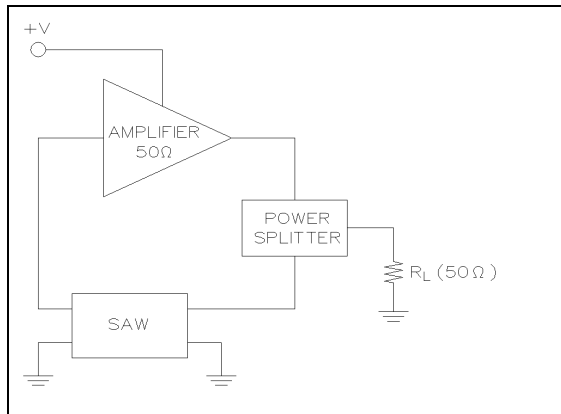
Figure 3. Two-Port SAW Oscillator Circuit

One-port (negative resistance) oscillators can offer greater design flexibility than 2-port designs. The chief advantage is that the circuit can be designed to optimize the current used in the oscillator transistor for the oscillator configuration chosen. Also one can more optimally match a transistor to the load via low-bandwidth, reactive networks than via resistive shunt feedback.   In a one-port design, the oscillator itself may be part of the matching structure which also simplifies the design. Although overall efficiency (η) of any oscillator

design depends on a wide range of variables, typically a one-port BAW oscillator can be many times more efficient and run at lower overall currents than a 2-port SAW based design. The circuits presented here can produce 0 dBm outputs with currents from 3 mA to 5 mA and useful outputs (-10 dBm) with as little as 0.6 mA of dc current. High-power (15 dBm) low current (11 mA) designs which are demonstrating >60% power efficiency at frequencies to 200 MHz using these new resonators are in development[*]. Another distinct difference between SAW devices and BAW (AT-cut) devices is the frequency versus temperature response. Figure 4 and Figure 5 are the temperature response curves respectively for the SAW and BAW devices.
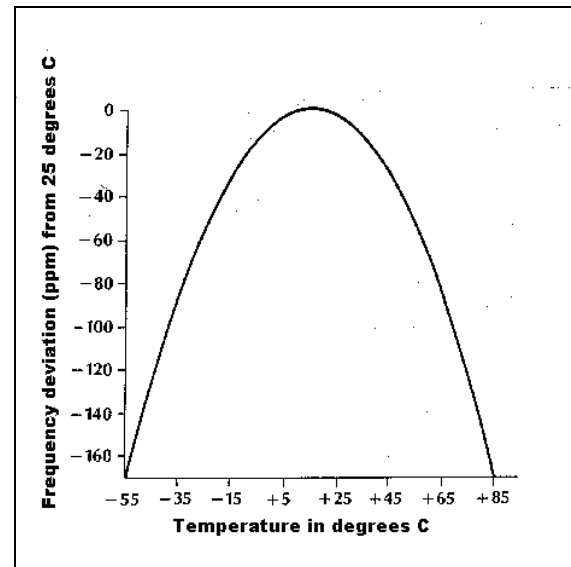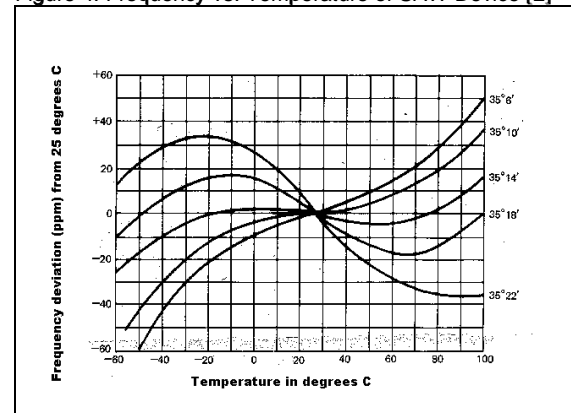
Figure 4. Frequency vs. Temperature of SAW Device [2]

Figure 5. Frequency vs. Temperature Curves for AT-Cut Resonator [3]

The AT-cut resonator temperature response is approximately three times less than the typical SAW temperature response. By careful selection of crystal angle one can obtain an AT resonator with temperature variations of less than ±10 ppm over a temperature range of -40° C to 75°. Finally, SAW devices can't be economically produced at low volumes because of the tooling cost to produce mask sets.

The ability to achieve fundamental frequencies up to 200 MHz with AT-cut BAW crystals can mean dramatic reduction in power consumption in many applications. Volume production costs typically compare to SAW devices, while sampling is far more economical.

Today good quality high-frequency transistors and passive components are readily available in low-cost, surface-mount packages. When these devices are used in conjunction with high frequency TmT resonators, many classic bulk-wave oscillator designs are realizable at high frequencies. These designs can be easily implemented with fundamental-mode resonator operation with no inductors in the circuit. To achieve higher frequencies (>200 MHz) use of resonator overtones and or frequency multiplication techniques can be used. These circuits become a little more complex and will require at least one inductor. Here are several examples.

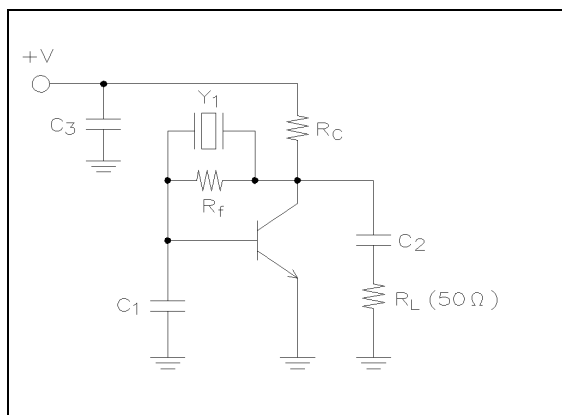## The Pierce Oscillator using a Fundamental Mode Resonator

Figure 6. Fundamental Mode Pierce Oscillator

The Pierce oscillator with fundamental mode resonator (Y_1) is shown in Figure 6. This circuit is probably the most popular oscillator design type and operates with the resonator as an inductive element. It provides a relatively low distortion sine wave to R_L if the oscillator is properly designed. The bias circuit is relatively stable and is easy to implement. R_C is chosen for the desired dc bias current and if R_f is chosen to be ~50 times R_C then the transistor will be biased with the collector voltage (dc) at approximately ½ of +V. The ratio of oscillation amplitude (collector to base) is approximately C_1/C_2. C_1 is usually chosen to dominate the transistor input impedance and therefore will be relatively large. The magnitude of X_{C1} should be in the 50 Ω to 200 Ω range. Making C_2 two to five times smaller than C_1 to creates a large amplitude of oscillation (at the collector) and a good impedance match to R_L. At the frequency of oscillation $|X_{C1}|+|X_{C2}|= |X_e|$ where X_e is the inductive reactance of the resonator Y_1, and X_{C1} and X_{C2} are the capacitive reactances of C_1 and C_2 respectively. The resonator is designed to be resonant with C_L which is $\dfrac{C_1 C_2}{C_1 + C_2}$ at the desired frequency [4]. For very precise designs C_1 or C_2 may be trimmed. Also varactor diodes can be used in combination with C_1 and/or C_2 to make the frequency voltage controlled and allow for temperature compensation.

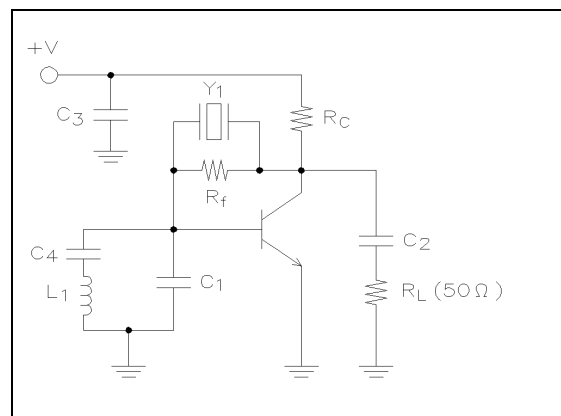## The Pierce Oscillator using a Resonator Overtone

Figure 7. Overtone Pierce Oscillator

An AT-cut resonator can be operated on an odd resonator overtone (typically the third or fifth) to achieve much higher frequencies. These overtones can be used if the fundamental at the desired frequency is difficult to produce or a higher Q resonator structure at the desired frequency is required for greater frequency stability. To convert the Pierce oscillator to resonator overtone operation, one must add a tank circuit to the basic design to select the desired overtone, Figure 7. This tank circuit is C_1 in parallel with L_1. C_4 is a high value dc blocking capacitor. L_1 and C_1 are chosen to be net capacitive at the desired overtone, usually the third. If this is true and the tank is inductive at the fundamental then this oscillator will run at the third overtone of the resonator. Select L_1 and C_1 such that: $\dfrac{1}{2\pi\sqrt{L_1 C_1}} > F_1$, where F_1 is the resonator fundamental, Also $\dfrac{X_{L1} X_{C1}}{X_{L1} + X_{C1}}$ should be made $-j50\Omega$ to $-j150\Omega$ at $3F_1$ where $X_{L1} = j\omega L_1$ and $X_{C1} = 1/(j\omega C)$.

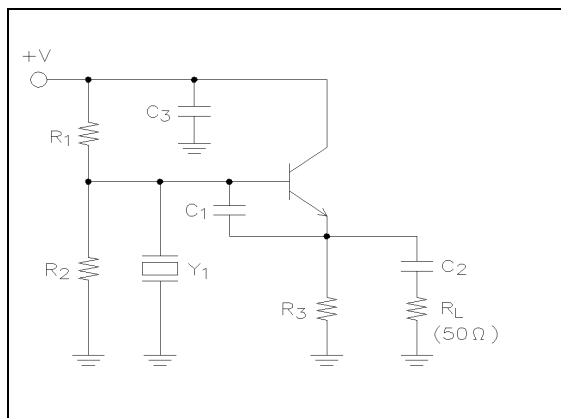## *The Colpitts Oscillator using a Fundamental Mode Resonator*

Figure 8. Fundamental Mode Colpitts Oscillator

The Colpitts oscillator, Figure 8, is another popular oscillator circuit which operates the resonator as an inductor. The Colpitts design has one side of the resonator tied to ground and like the Pierce design the resonator is resonant with the combination of C_1 in series with C_2 [5]. The series combination of C_1 and C_2, defined as C_L, is equal to $\dfrac{C_1 C_2}{C_1 + C_2}$. At circuit resonance, assuming the reactive elements dominate the circuit impedances, the base to emitter voltage gain provided by the tank (Y_1, C_1 and C_2), is $1+C_2/C_1$. The reactance of C_2 is usually chosen to be less than R_3 and greater than R_L. C_1 is usually chosen to be less than or equal to C_2. The transistor, used in an emitter follower configuration, must supply less than unity gain to sustain oscillation. The output can be taken directly off C_2. The load (R_L) could also be placed in series with the resonator as long as the resonator impedance is significantly larger than the load, R_L.

The Colpitts design can be designed to operate the resonator on an overtone. C_1 or C_2 must be replaced with an LC tank circuit using the same techniques described for the Pierce oscillator above.

The Pierce and Colpitts designs are the two most popular oscillator designs. They require few parts, are easy to design and are capable of high performance. VCXO (voltage controlled crystal oscillator) designs are commonly implemented with the Colpitts configuration. To achieve a broad tuning range it is desirable to have the varactor diode in series with the resonator. This is because this arrangement keeps the oscillator gain requirements and thus amplitude of oscillation constant over wide range of varactor capacitance. This is easily achieved in the Colpitts oscillator since one side of the resonator is normally connected to ground; where as the Pierce oscillator has the resonator placed in-between the load capacitors.

The Butler Oscillator

At very high frequencies, or overtone operation, it may be difficult to operate the resonator as a good, high Q, inductor. Therefore it becomes necessary to operate the

resonator near F_s where the resonator is approximately resistive and near its minimum impedance. Figure 9 is a Butler oscillator design. It is a series resonant design that also operates the resonator at low power levels.
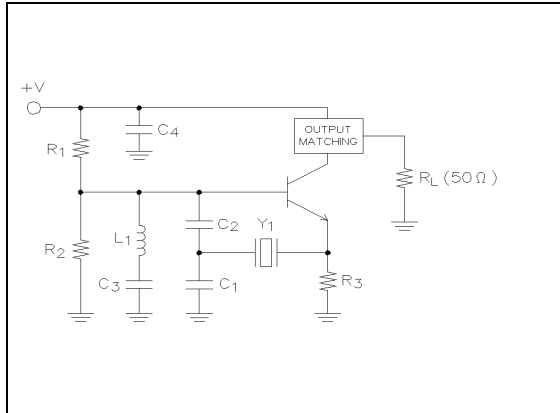

Figure 9. Butler Oscillator

This design uses a Colpitts structure (L_1, C_1, C_2) with the resonator completing the connection of C_2, and C_1 to the emitter. C3 is a dc blocking capacitor and has no real effect on the oscillation properties. In this case, at the oscillation frequency, the resonator will be approximately resistive and therefore near F_s. The LC tank, (L_1, C_2 and C_1), also selects the desired fundamental or overtone mode of the resonator. For this example, the output is taken off of the collector through an impedance matching network which could be a narrow-tuned tank circuit or transformer.

Frequency-Multiplying Oscillator Design

Incorporating TmT crystals and simple multiplication techniques crystal controlled frequencies to 1 GHz can be achieved. For the self-limiting oscillators described here the circuit nonlinearities will drive the loop-gain to one. These nonlinearities result in the generation of significant harmonic currents. If one designs a matching network to supply a poor match at the oscillator frequency and a very good match at some desired harmonic of the oscillator then frequency multiplication is achieved. It is desirable for maximum power efficiency to choose the harmonic with the greatest current since power goes with I^2. One

will generally lose approximately 10 dB of output power per successive harmonic. Therefore one should chose lower harmonics if power efficiency is a design issue.

The Butler oscillator design can be used as a frequency multiplying oscillator by matching the collector of the transistor to the load at a harmonic of the oscillator frequency, Figure 10.
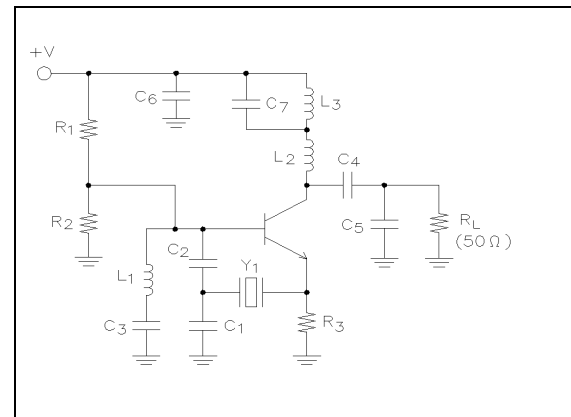

Figure 10. Frequency Multiplying Butler Oscillator

To eliminate the primary oscillator frequency from the output , L_2 is designed to resonate with C_7, L_3 is a choke and will look like a small capacitor at high frequencies in parallel with C_7. Since the collector of the transistor is shorted to ground at the oscillator frequency there will be no output power contribution at this frequency. An added benefit of having little or no primary frequency on the collector of the transistor is that this minimizes the Miller effect. The Miller impedance would effectively shunt L_1 with an impedance proportional to C_{cb} and the gain from base to collector. Minimizing Miller effects also helps decouple the oscillator from the load.

To make a frequency multiplier one must simultaneously design a tank circuit to shunt the oscillator current (primary) to ground and impedance match the desired harmonic to the load. At the desired harmonic L_2 and C_7 resonate with the combination of C_4, C_5 and R_L. The matching network therefore has a series resonant and a parallel resonant frequency. The higher order harmonics will be attenuated because successive harmonics naturally decrease in amplitude and the matching network will provide filtering. Thus the output will primarily be a single harmonic of the

oscillator frequency. Depending on the harmonics generated by the oscillator, the complexity of the matching network, the desired level of distortion, and overall efficiency of the circuit, one can pick any harmonic of the primary frequency. It may be necessary to shunt L_3 (choke) with a high value resistor (~5 kΩ) to damp a possible low frequency mode of oscillation caused by L_3 parallel resonating with C_4 at the collector node.

For simplicity, the oscillators presented here are not necessarily the most power efficient possible. Applying the following rules-of-thumb can dramatically improve the efficiency of any oscillator (or amplifier) design: 1) share bias currents by putting transistors in series; 2) design each transistor to perform more than one function; 3) switch transistors by using Class B or C configurations; 4) exploit the nonlinearities of the design or 5) combinations of the above.

The Differential-Amplifier Oscillator-Multiplier

An example of exploiting a nonlinearity for best efficiency or function can be demonstrated in a Pierce oscillator using a differential amplifier multiplier Figure 11.
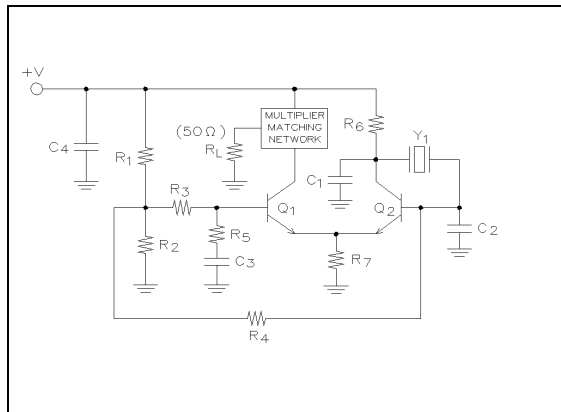

Figure 11. Differential-Amplifier Pierce Oscillator-Multiplier

This circuit is rather unique in that it has only one LC tank circuit (multiplier) but can provide frequencies to 1 GHz. This is because of the excellent multiplying properties offered by the differential amplifier (emitter-coupled pair). Q_1, Q_2 and R_7 are dc biased via R_1, R_2,

R_3 and R_4. The differential amplifier oscillator design will produce predominately odd-harmonics when driven heavily into compression. Therefore from a power efficiency standpoint this circuit can be an excellent tripler and a good quintupler. The odd harmonic generation also helps ease the design constraints on the multiplier tank because the adjacent harmonics are already suppressed.

Q_2 is the Pierce oscillator transistor which drives Q_1 via the emitter. To maximize the output power of this design, one must have a relatively large signal at the base of Q_2 to drive the differential amplifier into compression and generate the desired harmonics. To accomplish this C_1 and C_2 should be approximately equal in value. The multiplier tank will shunt the primary oscillator current to ground and impedance match the desired third or fifth harmonic to the load. Using a 200 MHz resonator with a tripler design for a 600 MHz output can produce approximately 0 dBm of output power with 5 mA dc current off a 3 to 5v supply. This design is capable of providing low harmonic distortion by suppressing all harmonics to at least 23 dB below the desired output.

When using microwave transistors in this circuit it may be necessary to place a small capacitor (~ 1 pF) from the emitters of Q1-Q2 to ground, via a short trace. This will limit the bandwidth of the circuit and thus dramatically reduce the possibility of undesired oscillation conditions that may exist near the cut-off frequency of the transistors.

The combination of miniature size, low power consumption and temperature stability afforded by oscillators using TmT resonators opens the door to new design approaches in small, portable, high frequency equipment. As more designers realize how simple it can be to convert low frequency bulk wave oscillators to high frequency designs incorporating these new devices, their use can be expected to increase at a rapid rate.

[*]Sandia National Laboratories has a proprietary design for high-efficiency, high-output power oscillators for frequencies to

approximately 200 MHz using BAW resonators. For more information call Kurt Wessendorf at 505-845-8817 or email at kowesse@sandia.gov; or for license agreement information contact Art Verardo at 505-843-4172 or email at aeverar@sandia.gov.

References

[1] M. E. Frerking, *Crystal Oscillator Design and Temperature Compensation*, Van Nostrand Reinhold 1978 pp. 20-30.
[2] Used by permission of Mark Stevenson, Sawtek Inc., Orlando, Florida.
[3] Used by permission Carl Maddalone, Chapman & Hill, Inc, New York, New York.
[4] M. E. Frerking, *Crystal Oscillator Design and Temperature Compensation*, Van Nostrand Reinhold 1978 pp. 56-63.
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Additional Reading

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