SAW Transmitters for Unlicensed Wireless

Surface-acoustic-wave resonators have been used to stabilize low power, unlicensed, wireless applications for over a decade. They operate keyless entries, door and gate openers alarm sensors, medical alert pendants, bar code readers, and many other applications. The author shows how different designs meet the specifications of several countries' unlicensed wireless regulations.

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Surface-acoustic-wave (SAW) resonatorlowpower transmitters have been in widespread use for unlicensed applications for more than a decade. Applications include automotive keyless entry, door and gate openers, wireless alarm sensors, medical alert pendants, bar code readers, and many others in the wireless remote control, security, and data transmission areas. There are important constraints that impact the transmitter configuration, including range, data rate, battery life, and size which must be judiciously accommodated if an optimum transmitter is to be designed. This paper will focus on the different types of SAW resonator stabilized low power transmitters and their performance characteristics.

There are many benefits to using SAW resonators in low power transmitters (in this paper, "low power" transmitters implies those which do not require a radio license for their use). First, they provide much better performance than LC resonators for transmitters, frequency synthesizers, or multiplied bulk crystal transmitters. The SAW resonator-stabilized oscillator, used in low-power transmitters, provides a very stable, fundamental mode frequency source at UHF. Properly designed SAW oscillators are relatively insensitive to changing load impedance and have good temperature stability. They are very rugged and, hermetically sealed in a TO-39 package, undergo minimal change with aging.

Since SAW resonators are a fundamental mode device circuit, their use can reduce transmitter complexity considerably, minimizing both overall transmitter size as well as cost. SAW devices also simplify product design and manufacturing by removing costly alignment steps, thereby yielding a very low cost/performance ratio.

However, to gain the maximum benefit from using a SAW resonator in the transmitter it is necessary to design around their characteristics from the beginning. Due to their fundamental mode of operation and high degree of temperature stability, SAW devices can be used to stabilize the operating frequency of both the receiver and the transmitter. Therefore, receiver bandwidths can be reduced, increasing sensitivity and decreasing susceptibility to interfering signals.

With the current burgeoning of wireless applications the finite amount of spectrum allocated to low-power devices is becoming more crowded. The use of SAW devices, whether resonators for frequency stability, or filters for rejection of out of band signals, is a very cost effective way to decrease the required system bandwidth.

SAW devices in wireless systems can reduce circuit complexity. This means that systems can be made smaller while retaining the performance advantages of larger and more complex systems. Additionally, a less complicated circuit results in lower power consumption, conserving precious battery resources. SAW devices make it possible to have a simple, low-power system, with no production alignment, that has performance characteristics that rival much more complex systems.

SAW resonators are fabricated by depositing a thin film of metal, typically aluminum, onto a highly polished quartz substrate. The frequency, Q, and insertion loss characteristics are primarily a function of the geometric pattern that is etched into the metal. Figure 1 shows a drawing of the different parts of a resonator.

The SAW transducer is used to convert an electrical signal to an acoustic wave that propagates along the surface of the substrate. The periodicity of the electrodes on the surface of the substrate are used to determine the frequency response of the SAW device.

SAWs can be fabricated on many different types of piezoelectric substrates. There are Lithium Niobate and Lithium Tantalate used for wide band SAW filters, and Quartz used for narrow-band SAW filters and resonators. Of these, quartz is the most temperature stable.

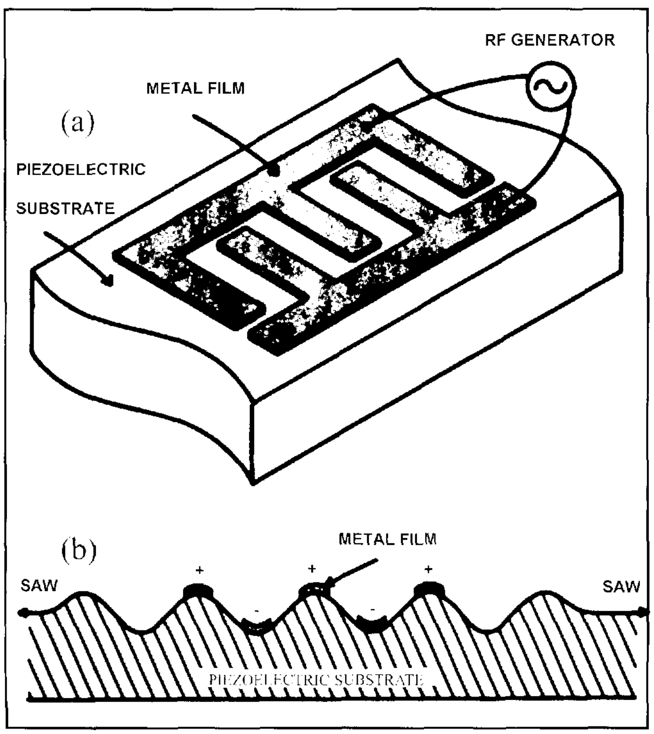

Figure 1. Interdigital SAW transducer used as a resonator.

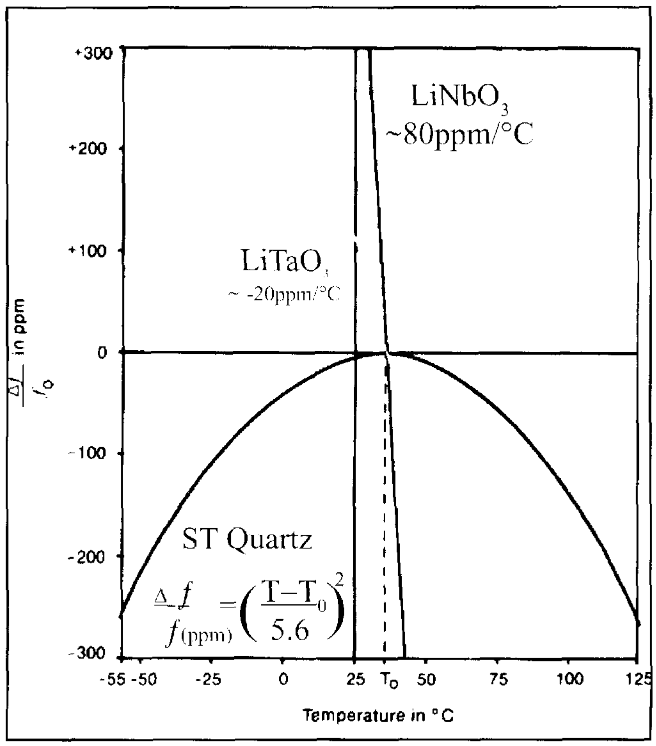

Figure 2. Temperature characteristics of various SAW materials.

The frequency of the SAW resonator, and therefore that of the oscillator, exhibits the parabolic dependence on temperature described by the equation in Figure 2. For a typical transmitter, designed to operate from -40C to +85C, the change in center frequency would be approximately 125 PPM, an average of only 1 PPM/C, about the temperature coefficient of invar steel and twenty times more stable than a resonator fabricated of aluminum.

This change in operating frequency is at a minimum when the SAW resonator has its turnover temperature centered in the operating temperature range. The turnover temperature is set during the design of the SAW resonator and can be varied using different cuts of quartz substrates. The numerical constant, 5.6 , in the denominator of the T_0 equation is an empirically derived term that is dependent on the packaging and mounting material used in the construction of the SAW resonator.

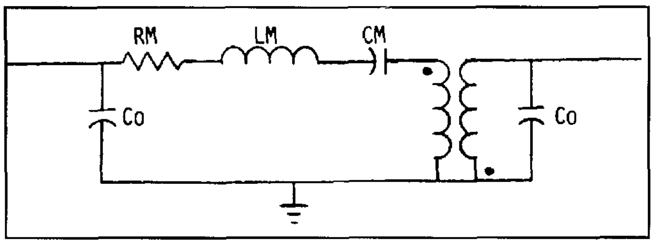

Figure 3. Two-port equivalent circuit for SAW resonator.

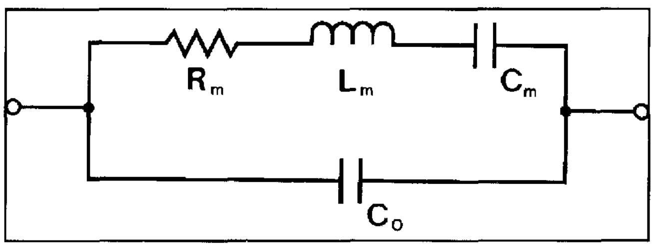

Figure 4. One-port SAW equivalent circuit

SAW resonators can be modeled by an equivalent circuit using lumped elements. Figures 3 and 4 show the equivalent circuit for two commonly used SAW resonators. Figure 3 is the equivalent circuit for a two-port single-pole resonator. This model is valid near the center frequency of the SAW resonator. The phase shift through this device can be set to either 0 or 180 degrees which is depicted with the ideal transformer. The motional resistance, RM, capacitance, CM, and inductance, LM, are used to describe the frequency response of the device. Static transducer capacitance and package parasitic capacitance is lumped into the capacitors labeled C_0. C_0 introduces an additional phase shift that results in a phase that is not exactly 0 or 180 degrees at the center frequency.

The equivalent circuit for the more common one-port resonator is shown in Figure and has the same components as the two-port model. The main difference is that the static capacitance, C_0, is in parallel with the resonant arm of the device. This has important implications when using this device in an oscillator design.

These one-port resonators are commonly used as the frequency determining element in a Colpitts oscillator. This oscillator topology is the most popular one found in low-power transmitters. Figure 5 shows the reactance versus frequency of a single-port SAW resonator. This plot can be used to determine the operating frequency of the circuit. The frequency of oscillation will be at the low reactance point near the real axis. The exact frequency will depend on the circuit tuning.

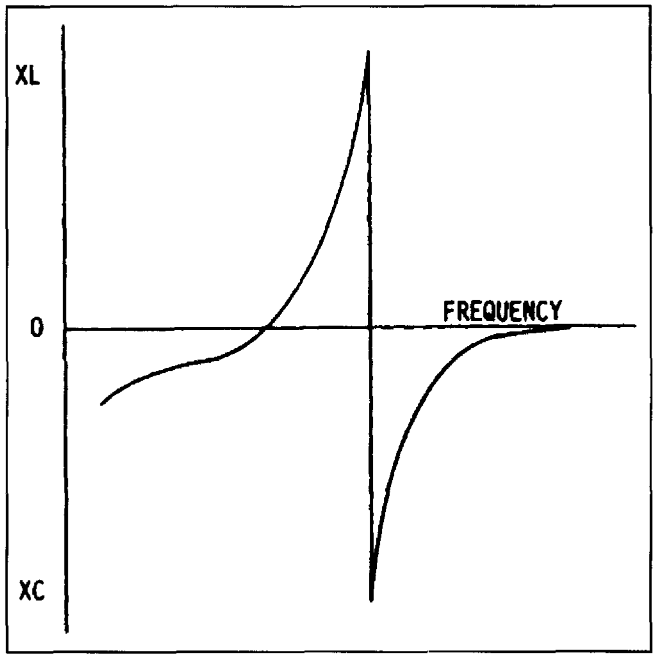

Figure 5. Reactance versus frequency of a single-port SAW resonator.

The effect of C_0 can be seen as negative reactance, at frequencies considerably distant from the anti-resonant point of the plot. At both lower and higher frequencies the resonator has a net capacitive reactance. It is very important to design the circuit so that it does not present a equal magnitude inductive reactance to the resonator in these frequency ranges, because then the oscillator might run as a simple LC oscillator at one of these frequencies. The operation then would not be dominated by the SAW resonator but rather would have only the characteristics of an LC oscillator.

Figure 6 shows the schematic diagram of the first generation SAW transmitter. The circuit uses the Colpitts oscillator topology. The printed loop antenna is used as the tuning inductor with the feedback accomplished with the collector to emitter capacitor. The feedback is adjusted such that the gain of the circuit is not sufficient to cause oscillation at frequencies other than the SAW frequency, or so small that the oscillator does not modulate properly. The printed loop antenna, or inductor, should be designed to resonate with the parallel combination of the output capacitance of the transistor, and the series equivalent of the collector-emitter and emitter to ground capacitors.

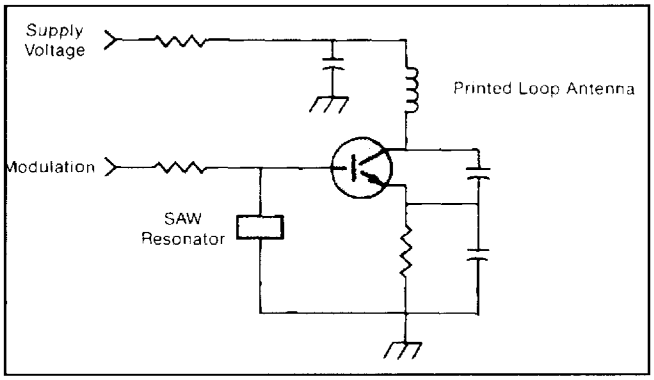

Figure 6. First generation SAW transmitter.

There are several advantages to this circuit. It requires no production tuning, has a minimum parts count, and can be designed to meet the FCC Part 15 specification (for unlicensed transmitters) particularly those related to harmonics. For these reasons it has been a popular and reliable oscillator for applications that fall under FCC Part 15.

However, there are some limitations to this design. Due to the high Q of the resonator, the data rate is limited to a maximum of about 3 KHz (or a pulse width of 167 microseconds). The transmitter frequency is also sensitive to component tolerances and parasitic reactance contributed by the PC board layout. An additional problem is encountered when this circuit is employed in a transmitter that will be subject to European emissions regulations, which are much more stringent in the allowable level of the harmonics than is the FCC Part 15. The chart shown in Figure 7 highlights the important differences in the various regulations.

The series fed antenna, typically a trace on the circuit board, does not provide enough frequency selectivity for the transmitter to meet the more stringent regulations. There are some design techniques that can help, such as using a lower frequency transistor, but its limited frequency response further reduces the maximum data rate. A trap can be employed at the second harmonic, but this typically requires an alignment step in manufacturing. Both of these options set further constraints on the transmitter design.

In order to comply with the European regulations, specifically the DTI MPT1340 of the United Kingdom, a variation of the first generation transmitter operating at a fundamental frequency of 418 MHz (Figure 8) was developed. Like its predecessor, it is a Colpitts oscillator; but, to reduce the harmonic emissions to the required level, it has two modifications. First, the fundamental output power is reduced and with it the level of the second harmonic. This reduces the amount of filtering required to satisfy the specification. Second, the addition of two adjustments is included. One adjustment is used to set the oscillator on frequency and the other to tune the antenna. This design makes use of a tapped antenna which has a higher impedance, allowing the Q of the tuned antenna circuit to be made higher. This higher Q circuit offers more rejection at the second harmonic. The reduction of fundamental power and use of a higher impedance antenna are typical techniques used in most of the transmitter designs for the European market.

COUNTRY	REGULATION	FREQUENCY LIMITS (MHz)	FUNDAMENTAL POWER	2nd HARMONIC	3rd HARMONIC	GREATER THAN 3rd
UNITED KINGDOM	DTI MPT1340	417.9 - 418.1	250uW	4nw	1uW	1uW
GERMANY	FTZ 17 TR 2100	433.05 - 434.79	25mW	1nW	30nW	30nW
FRANCE	CNET PAA1542	224.6 - 224.8	5mW	250nW	4nW	250nW
NETHERLANDS	PTT	433.052 - 434.797	50uW	4nW	1uW	1uW
JAPAN	MPT	303.675 - 303.975	500uV/m	35uV/m	35uV/m	35uV/m
U.S.	FCC PART 15	260 - 470	3750-12500 uV/m	375-1250uV/m	375-1250uV/m	375-1250uV/m

Figure 7. Low power (unlicensed) system regulations for various countries.

However, even this design does not reliably satisfy the German FTZ 17TR2100 emissions requirements. A further reduction in output power would be required for this design to pass the more stringent second harmonic specification, undesirable because of its negative impact on system range.

The need for greater power, reduced harmonic levels, and no adjustments gave rise to a new design approach for low-power transmitters. This design uses the Pierce oscillator configuration shown in the block diagram of Figure 9.

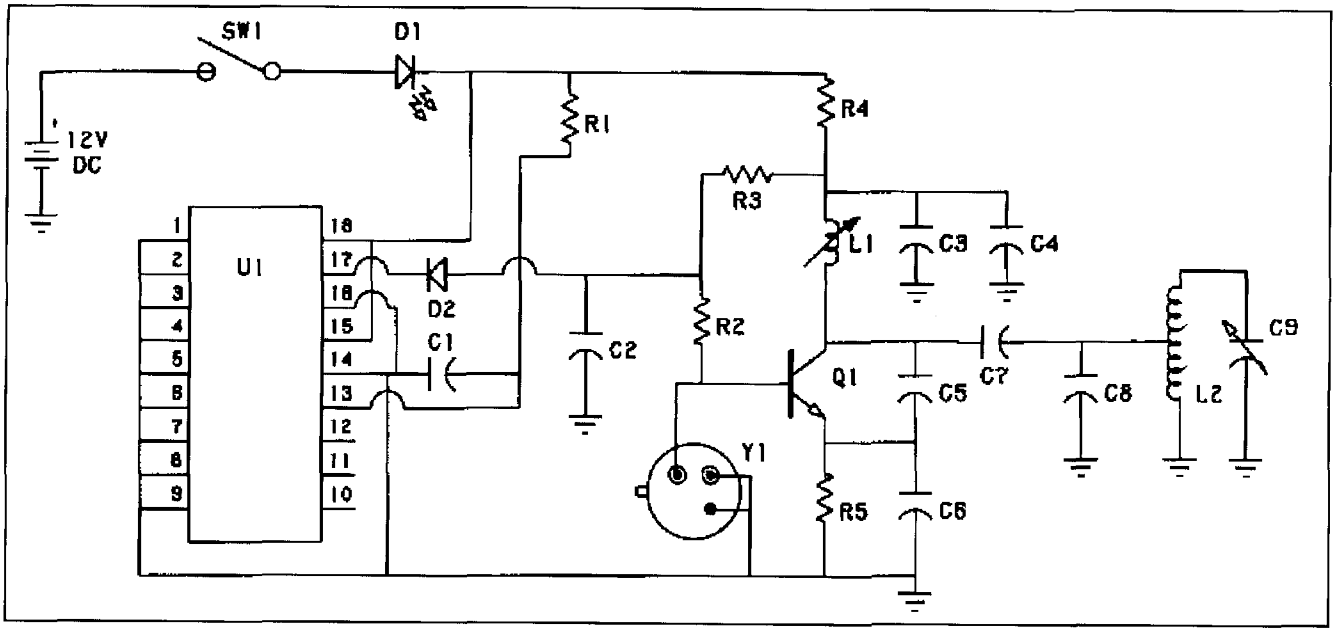

Figure 8. A modified Colpitts SAW oscillator to DTI MPT1340.

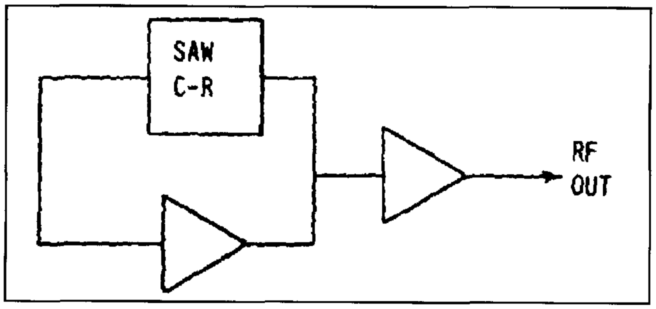

Figure 9. Pierce oscillator block diagram using SAW coupling.

In order to implement this circuit we developed a SAW coupled resonator, having a two-pole frequency response similar to that shown in Figure 10. This is contrasted with Figure 11 which shows the response of a standard single-pole resonator at the same frequency. Perhaps the most important difference between the two devices is the amount of phase shift across the 3 dB bandwidth, the single-pole standard resonator having only 90 degrees of phase shift and the two-pole having 180 degrees.

Referring to the block diagram in Figure 9, the requirement for oscillation is that the gain around the loop be at least unity with a phase shift of 0 or an integer multiple of 360 degrees. This is commonly referred to as the Barkhausen criteria.

The importance of the extra 90 degrees of phase shift

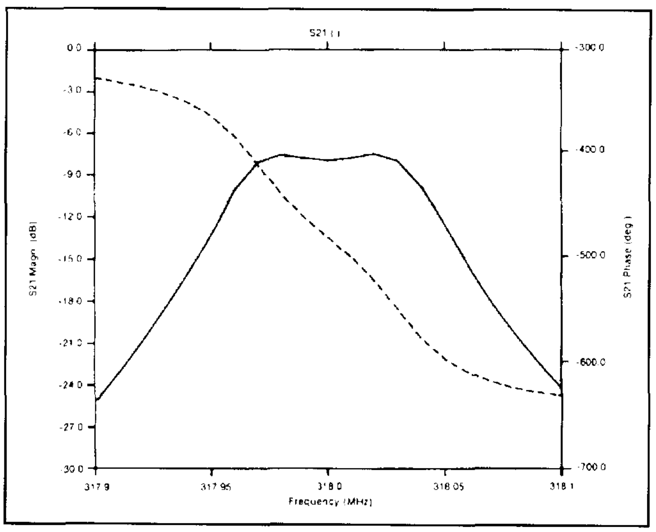

Figure 10. Coupled-Resonator. Insertion Loss: -7.5dB. 3dB Bandwidth: 82KHz. Phase Variation Over 3dB Bandwidth: 180 Degrees. Loaded "Q": 3878.

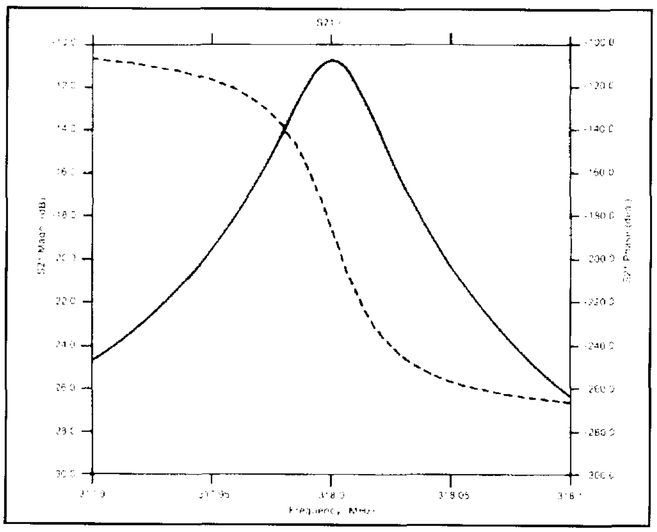

Figure 11. Two-port Resonator. Insertion Loss: -10.8dB. 2dB Bandwidth: 36KHz. Phase Variation Over 3dB Bandwidth: 90 Degrees. Loaded "Q": 8833

across the SAW coupled resonator bandwidth can be illustrated with the following example.

The phase shift through a standard transistor amplifier at UHF is approximately 240 degrees. In order for this circuit to meet the phase requirement, the phase shift provided by the feedback element must be either +120° or -240°. Usually a single-pole resonator has either 0° or 180° of phase shift at the center frequency with a +/-45° phase shift across the 3 dB bandwidth. Thus, the phase criteria would not be met within the 3 db bandwidth of the resonator.

The coupled resonator, on the other hand, has a similar absolute phase at the center frequency, 0° or 180° but has a +/-90° phase shift across the 3 dB bandwidth. Using a coupled resonator and a properly designed amplifier, it is possible to assure that the oscillator frequency will be within the 3 dB bandwidth of the SAW. The benefit of this topology is that it requires no tuning and is relatively insensitive to parasitic reactance. In contrast, if a single port resonator were used, it would be necessary to introduce an added phase shift circuit to the oscillator loop to obtain the required phase shift.

Using this approach, we designed an integrated circuit transmitter, a block diagram of which is shown in Figure 12. This circuit is designed for FCC Part 15 applications and is compatible with all current and proposed FCC Part 15 regulations.

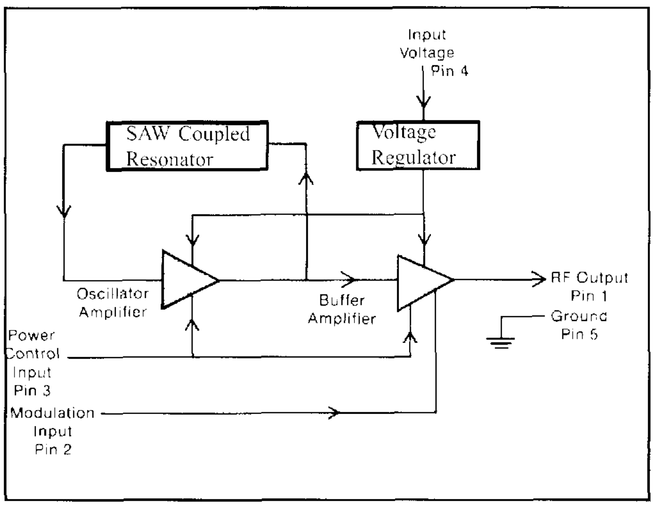

Figure 12. Block diagram of the 318 MHz integrated circuit wireless transmitter using a two-pole SAW resonator.

A buffer amplifier is used so that the oscillator frequency is insensitive to changes in load parameters. The buffer amplifier also allows for a much higher modulation rate than would be possible if the oscillator were to be directly modulated. The design goals and actual performance are shown in Figure 13.

SPECIFICATION	DESIGN GOAL	TYPICAL MEASURED PERFORMANCE
Output Frequency	318.000 MHz +/- 250 KHz	318.000 MHz +/- 100 KHz
RF Output Power (50ohm Load)	>= +7 dBm	+ 12 dBm
Power Output Variation over a Supply Voltage Range 6.0 to 10.0 V	+/- 1 dB	+/- 1 dB
Modulation Depth (On/Off Ratio)	35 dB Min	> 50 dB
Modulation Rate Capability	< 50 KHz	< 50 KHz
Modulation Rise or Fall Time	< 1 µsec	<1 µsec
Radiated Harmonics when used with RFM Specified Antenna	-20 dBc	-20 dBc
Ouput Power Control Adjustment Range	15 dB	10 dB
Power Supply Current Drain at 10 V and Maximum Power	<25 mA	<20 mA
Power Supply Current Drain at 10 V and Power Control Resistor Grounded	< 1 µA	< 10 µA

Figure 13. Typical performance and design goals for the 318 MHz wireless transmitter stabilized with a two-pole SAW resonator.

This transmitter design accommodates the maximum amount of output power allowed under FCC Part 15 while meeting the emissions specification. Also, it operates with a high data rate, up to 50 KHz., and requires no production tuning. The disadvantages of this design are its relatively high power consumption, a limit on battery powered applications, and its relatively high harmonic levels, limiting European applications.

A demonstration transmitter was developed to confirm that the more rigid European harmonic specifications could be satisfied using the two-pole SAW design just described (Figure 14). Although it requires an adjustment to center the antenna circuit, this design meets the European emissions standards with only one, not two production adjustments.

To address the special emissions requirements of the European standards as well as US applications requiring a high degree of miniaturization we developed a third generation of transmitter component. This transmitter component is a fully functional RF building block that design engineers, some of whom may have little RF background, can incorporate easily into a wireless transmitter application.

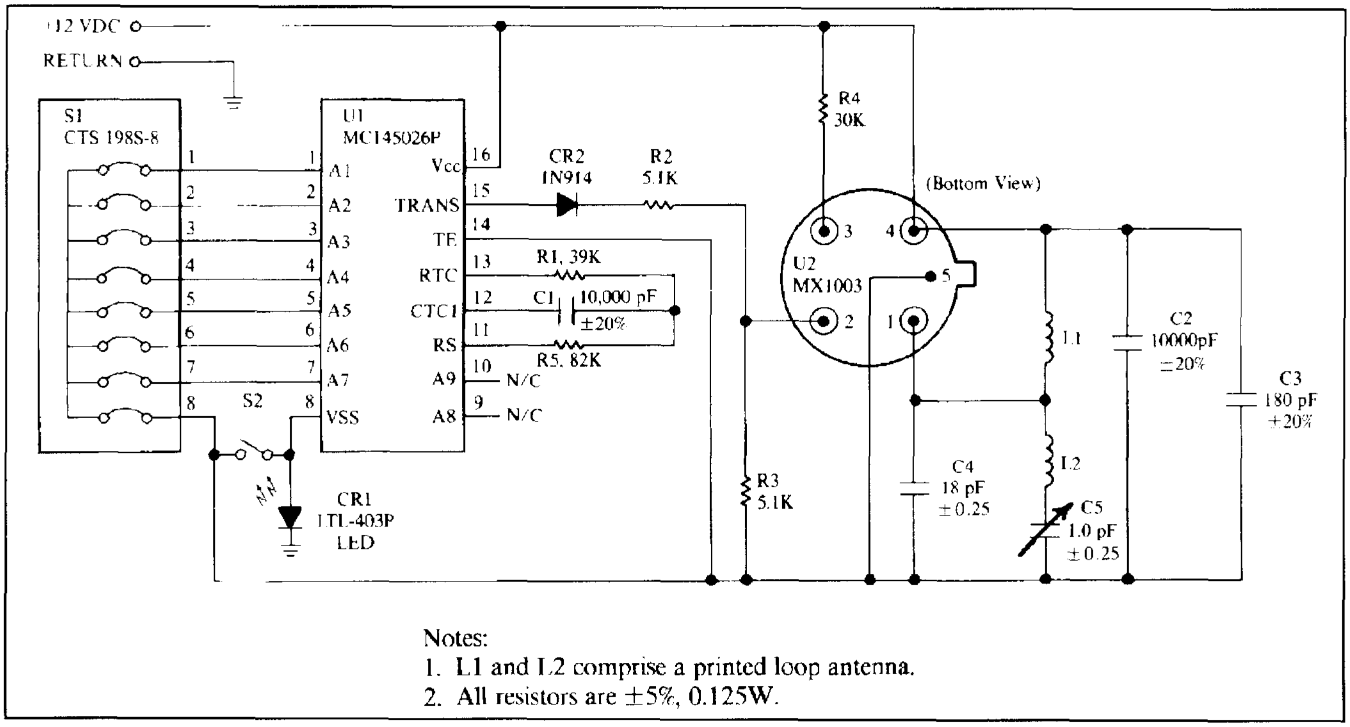

Figure 14. Schematic diagram for a transmitter which meets the European emission standards while requiring only one production tuning adjustment.

The miniature passkey sized hybrid transmitter is packaged in a hermetically sealed surface mount package. The block diagram of the transmitter is shown in Figure 15. The oscillator topology is a Pierce configuration using a SAW coupled resonator as the feedback element. Like the micro-transmitter THIS transmitter is also very insensitive to changing load conditions and parasitic reactance.

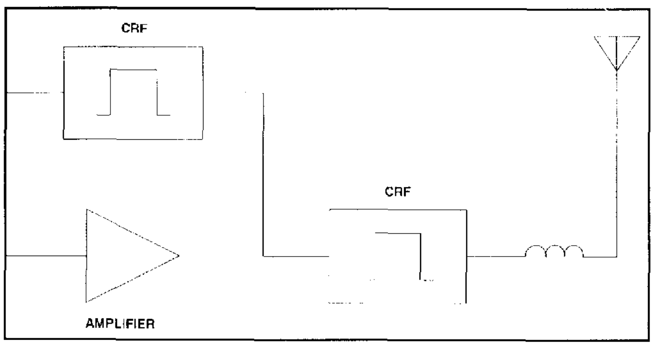

Figure 15. Block diagram of the miniature passkey transmitter. The antenna is formed using a portion of the key as an aerial.

Recent advances in SAW technology now yield coupled resonator designs that have 3-5 dB of insertion loss, untuned, in a 50 Ohm test fixture, at frequencies as high as 930 MHz, greatly simplifying the oscillator circuit and permitting a very cost effective transmitter building block. This low loss coupled resonator can also been used as the output filter for a wireless transmitter. With this approach the fundamental output power of the transmitter can be high and still provide the necessary harmonic rejection. This also allows that the transmitter's output power can be made as high as possible in a circuit design requiring a minimum amount of power supply current, extending battery life.

Figure 16 shows the specifications of a hybrid transmitter designed to meet the German market. This module, when properly incorporated in a wireless transmitter, meets the German FTZ 17 TR2100 emissions requirements, as evidenced by the demonstration unit whose data is shown in Figure 17.

Characteristics	Minimum	Typical	Maximum	Units
Operating Frequency	433.72	433.92	434.12	MHz
RF Output Power	25	50		µW
Spurious Emissions				
Power Supply	2.7	3	3.3	Volts
Operating Current		7	10	mA Peak
Operating Tempature	-30		85	C
Data Rate		1		KHz
Oscillator Turn On Time			100	µs
Oscillator Turn Off Time			100	µs

Figure 16. Performance of the keyhead wireless transmitter which meets the German specifications for emission.

Harmonic	Freq (MHz)	Power Measure (dBm)	Power Measure (watts)	FTZ Spec (Watts)	DTI Spec (Watts)
Fund.	433.92	-12	63E-6	25E-3	250E-6
2nd	867.84	-60	1E-9	1E-9	4E-6
3rd	1301.7	-65	0.3E-9	30E-9	1E-6
4th	1735.6	-62	0.6E-9	30E-9	1E-6
5th	2169.7	-46	25E-9	30E-9	1E-6
6th	2603.5	-49	13E-9	30E-9	1E-6
7th	3037.4	-47	20E-9	30E-9	1E-6
8th	3471.3	-48	16E-9	30E-9	1E-6

Figure 17. Performance of a 3 volt lithium battery powered keyhead transmitter using a surface mount transmitter module.

A hybrid transmitter (Figure 18 performance) designed to operate from a 3 volt Lithium battery power source is configured as the head of an ignition key and uses the key stem as the antenna. This configuration yields maximum performance when compared to previous unlicensed, low-powered transmitter designs.

Acknowledgment

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