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APPLICATION NOTE 4929

Adapting Low-Band ISM Transmitters for High-Band Operation

Aug 23, 2011

Abstract: ISM 300MHz to 450MHz band RF transmitters already serve the European 434MHz market, as well as the most important frequencies in the U.S. 260MHz to 470MHz band. This application note explores whether an 868MHz transmitter can be created from existing 300MHz to 450MHz RF IC products. An 868MHz transmitter would serve Europe's license-free band from 868MHz to 870MHz. Specifically, the article discusses a series of tests and analyzes how much power can be transmitted at 868MHz from one or more of the ISM-band RF transmitters designed for the 300MHz to 450MHz ISM band.

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Introduction

Low-band (300MHz to 450MHz) ISM RF transmitters already serve the European 434MHz market, as well as the most important frequencies in the U.S. 260MHz to 470MHz band. This application note explains how an 868MHz transmitter can be created from existing low-band RF IC devices to serve Europe's license-free 868MHz to 870MHz band.

Wireless Technology Overview

Click here for an overview of the wireless components used in a typical radio transceiver.

The article specifically discusses a series of tests and analyzes how much power can be transmitted at 868MHz from one or more of the ISM-band RF transmitters designed for the 300MHz to 450MHz range.

The Theoretical Challenge

The switching power amplifier (PA) in most low-band ISM transmitters produces a second harmonic that is only 3dB below the fundamental frequency. If some efficiency and power can be sacrificed, would it be possible to create a serviceable 868MHz ASK transmitter from an IC designed for 434MHz operation? Since the phase-noise density is just low enough to meet the European Telecommunications Standards Institute (ETSI) out-of-band emission standards at Europe's 434MHz license-free band, the phase-noise density would not meet the more stringent requirements for the 868MHz band. However, that does not mean that there is no value in devising an 868MHz ASK transmitter. Some customers will have applications for very low transmitting power, or perhaps some modifications can be made to the oscillator on the low-band ICs without the need a completely new design?

RF Spectrum of a Switching Power Amplifier

The switching PA found in most ISM low-band RF transmitters produces a periodic series of 0.25 duty-cycle pulses, where the pulse period is the period of the carrier frequency. The theoretical frequency spectrum of this pulse train is a set of evenly spaced lines at multiples of the carrier frequency. The amplitude of each line

is weighted by a sinc (sinx/x) curve that contains zeroes at multiples of 4 times the carrier frequency. **Figure 1** illustrates the first six lines of the spectrum for a 434MHz carrier frequency. The amplitude of the 868MHz component (the second harmonic) is only 3dB down from the fundamental 434MHz component. In practice, the switched amplifier drives a tuned circuit, whose characteristics depend on the desired rejection of the harmonics of the fundamental frequency. If the tuned circuit has a relatively wideband characteristic, it should radiate the 868MHz component at a power level that is not much more than 3dB below the fundamental frequency.
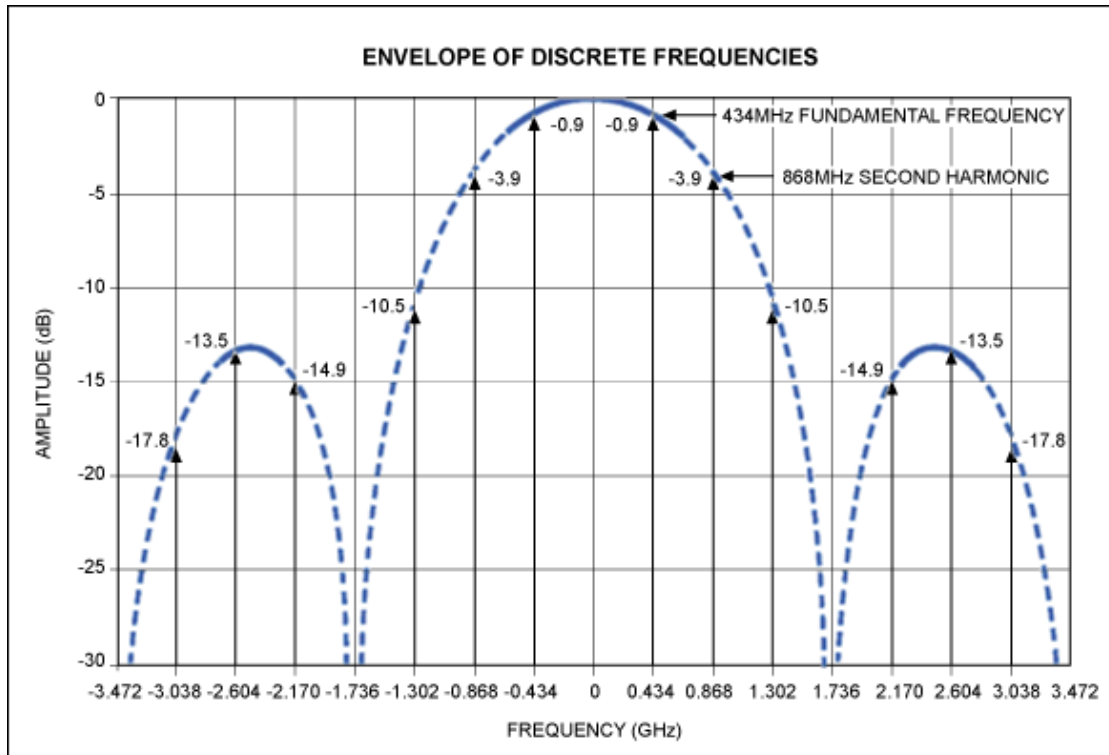

Figure 1. Theoretical power contribution from fundamental and harmonics of a 25% duty-cycle RF pulse train at 434MHz.

The 3dB difference was verified by removing the harmonic filter from a MAX7044EVKIT and changing the bias inductor to 62nH, a value that resonates with the approximately 2pF to 2.5pF of stray capacitance. The resonant circuit formed by this L-C combination has a wide bandwidth. Thus, it does not attenuate the 868MHz harmonic significantly when the PA output is connected directly to a 50Ω load. **Figure 2** shows the spectrum analyzer trace of the 434MHz and 868MHz components. The 868MHz component is 3.5dB lower than the 434MHz component, which represents only 0.5dB reduction by the resonant circuit.
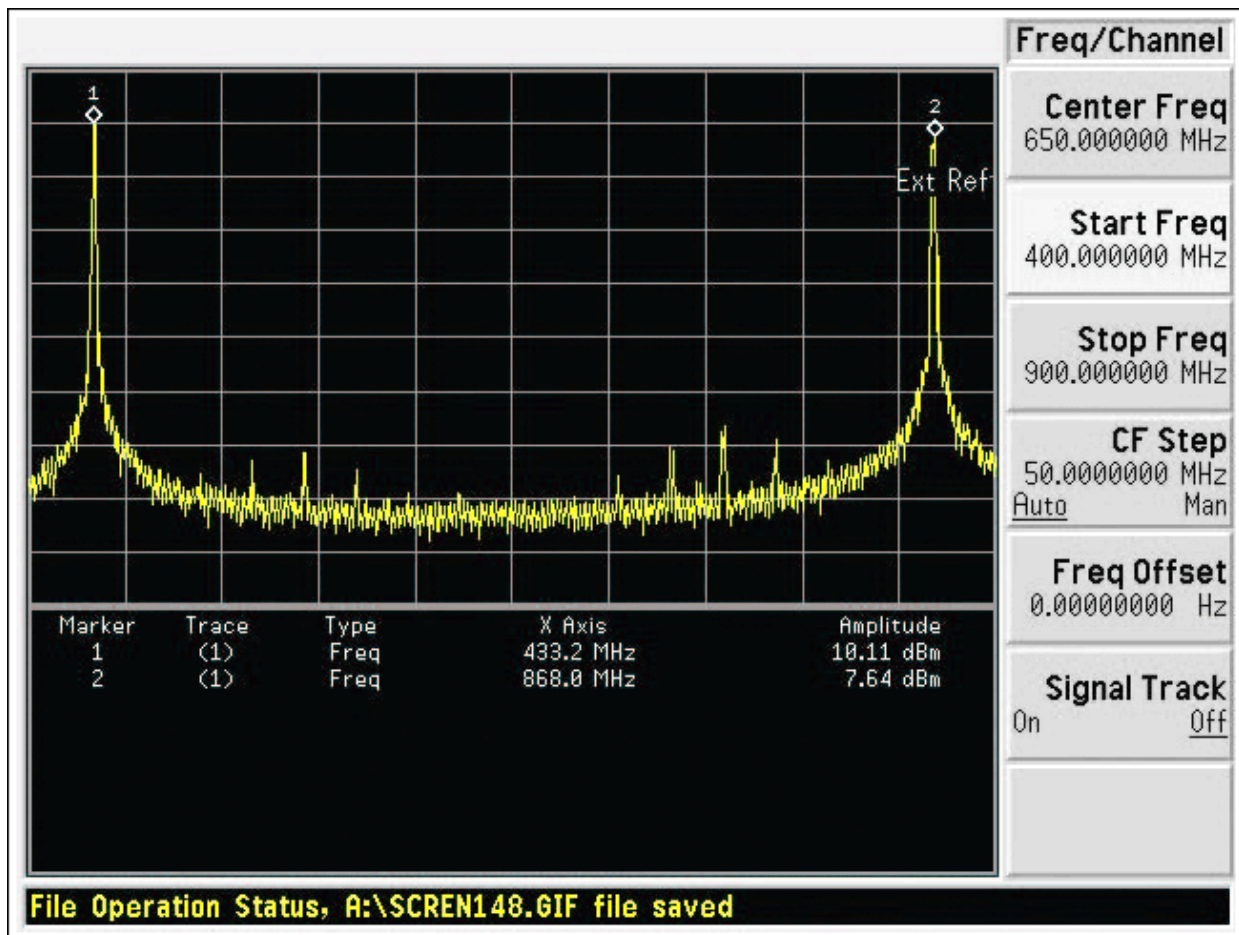
Marker	Trace	Type	X Axis	Amplitude
1	(1)	Freq	433.2 MHz	10.11 dBm
2	(1)	Freq	868.0 MHz	7.64 dBm

Figure 2. Spectrum of MAX7044EVKIT ISM transmitter with tank circuit tuned to 434MHz.

The next step is to modify the matching-network components to enhance the 868MHz second harmonic and attenuate the 434MHz fundamental frequency.

Modification of Antenna-Matching Circuitry for 868MHz Operation

Matching-Network Topology for 434MHz Operation

The MAX7044EVKIT was modified for 868MHz operation, using the component topology already in place for 434MHz operation. The matching networks of all the ISM RF transmitter EV kits in the 300MHz to 450MHz band have the same topology, shown in **Figure 3**. The reference designators are identical to those in the MAX7044EVKIT.
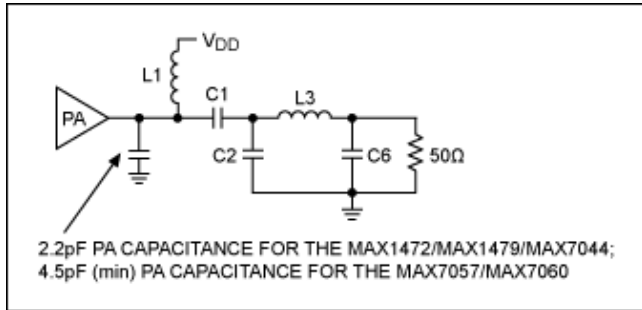
Figure 3. Matching-network and reference designators for the MAX7044EVKIT.

There are several ways to realize a matching network to a 50Ω load with this topology. The most straightforward method is to populate the C2-L3-C6 pi network as a 50Ω lowpass filter for harmonic rejection. Next, use the C1-L1 combination as an "L" narrowband impedance transformation network that converts 50Ω to a higher impedance. With the exception of the MAX7044 and MAX7060 280MHz to 450MHz programmable transmitter, all Maxim ISM RF low-band transmitters are the most power efficient when they drive an impedance between 125Ω and 250Ω. The MAX7044 achieves its highest power in the low band (13dBm with 2.7V supply) when it drives a 50Ω to 60Ω load. Lower power levels and lower supply currents can be achieved by increasing the impedance presented to the transmitter PA output. For normal operation in the low band, the inductors and capacitors are chosen to present the desired impedance to the PA at the design frequency. For the MAX7044EVKIT, the values chosen present a good match to 50Ω at 433.92MHz.

The purpose of the experiments that follow is to change the matching components in a 433.92MHz EV kit (to present a good match at 868MHz) and to reduce the transmitted power at 434MHz.

PA-Output Tank Circuit Tuned to 868MHz

The first step in developing a matching network for 868MHz is to try the simplest possible match, which is an 868MHz tank circuit at the PA output, connected to a 50Ω resistor. This approach is used to produce the baseline spectrum in Figure 1. However, in this case the bias inductor is chosen to resonate the stray capacitance of the PA pin at 868MHz (instead of 434MHz). To produce the schematic presented in **Figure 4**, the PA bias inductor was changed in the MAX7044EVKIT from 62nH (for a resonant circuit at 434MHz) to 16nH (for a resonant circuit at 868MHz). Additionally, the shunt capacitors were removed from the pi network and the series inductor was replaced with a 0Ω shunt. Finally, the series capacitor C1 was changed between the pi network and bias inductor to 47pF, effectively a DC block at 868MHz.
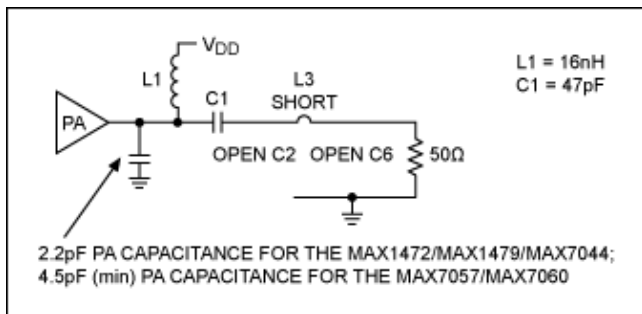

Figure 4. Simple tank-circuit matching network for the MAX7044EVKIT at 868MHz.

Power measurements of the 434MHz fundamental frequency and the first four harmonics are listed below. The spectrum of the 434MHz and 868MHz components is shown in **Figure 5**. Frequencies are rounded off to the nearest 1MHz.

V_{DD} = 2.7V, I = 16.83mA, I_{PLL} = 2.06mA, I_{PA} = I - I_{PLL} = 14.77mA
P(434MHz) = +9.0dBm

P(868MHz) = +8.65dBm
P(1302MHz) = +4.5dBm
P(1736MHz) = -3.0dBm

Total PA efficiency (power in all four frequencies/(V_{DD} × I_{PA})) = 46.6% The 868MHz PA efficiency = 18.4%
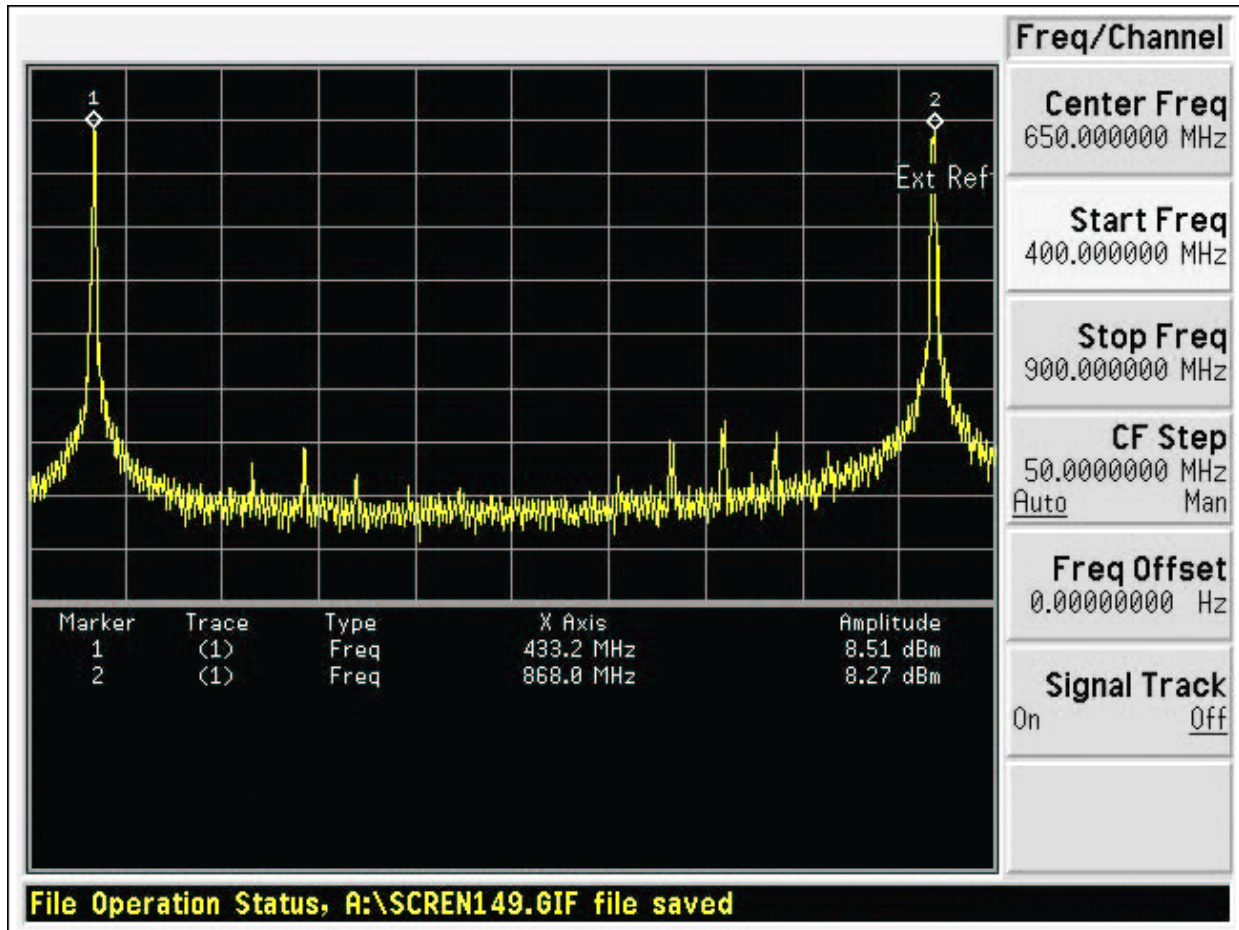

Figure 5. Spectrum of MAX7044EVKIT with tank circuit tuned to 868MHz.

Because the bandwidth of the 868MHz tank circuit is narrower than the bandwidth of the 434MHz tank circuit (the stray capacitance remains the same, so the inductor needs to be reduced by a factor of 4), there is enough rejection of the 434MHz fundamental frequency to make the power in the fundamental and second harmonic almost equal. This simple change in the tank circuit improves the power ratio of the 868MHz component to the 434MHz component by approximately 3dB.

Highpass Match for 868MHz

The next step is to change the lowpass pi network to a highpass network to further attenuate the 434MHz component. The 16nH PA bias inductor and the series capacitor (47nH) were not changed. The pi network, typically used as a lowpass filter for higher harmonic rejection, was changed to a simple highpass L network that transformed 50Ω at the antenna connector to 200Ω at the PA output pin. The simpler L network was chosen for this step, instead of a full pi network, to minimize the number of additional component changes and determine the effectiveness of this change. Because the load seen at the PA output using the L network is 200Ω (instead of 50Ω), the Tx-power current drain should be lower than it is for a 50Ω load.
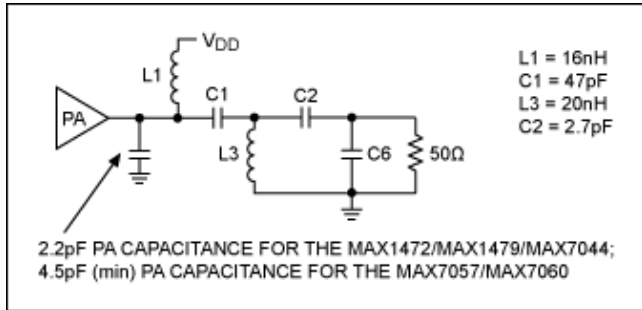
Figure 6. Highpass L impedance transformation network.

Power measurements of the 434MHz fundamental frequency and the first four harmonics are listed below. The spectrum of the 434MHz and 868MHz components is shown in **Figure 7**. Frequencies are rounded off to the nearest 1MHz.

V_{DD} = 2.7V, IDC = 18.1mA, I_{PLL} = 2.06mA, I_{PA} = IDC-I_{PLL} = 16.04mA
P(434MHz) = +2.5dBm
P(868MHz) = +11.2dBm
P(1302MHz) = +4.0dBm
P(1736MHz) = -3.2dBm

Total radiated efficiency (all four frequencies) = 41.5%
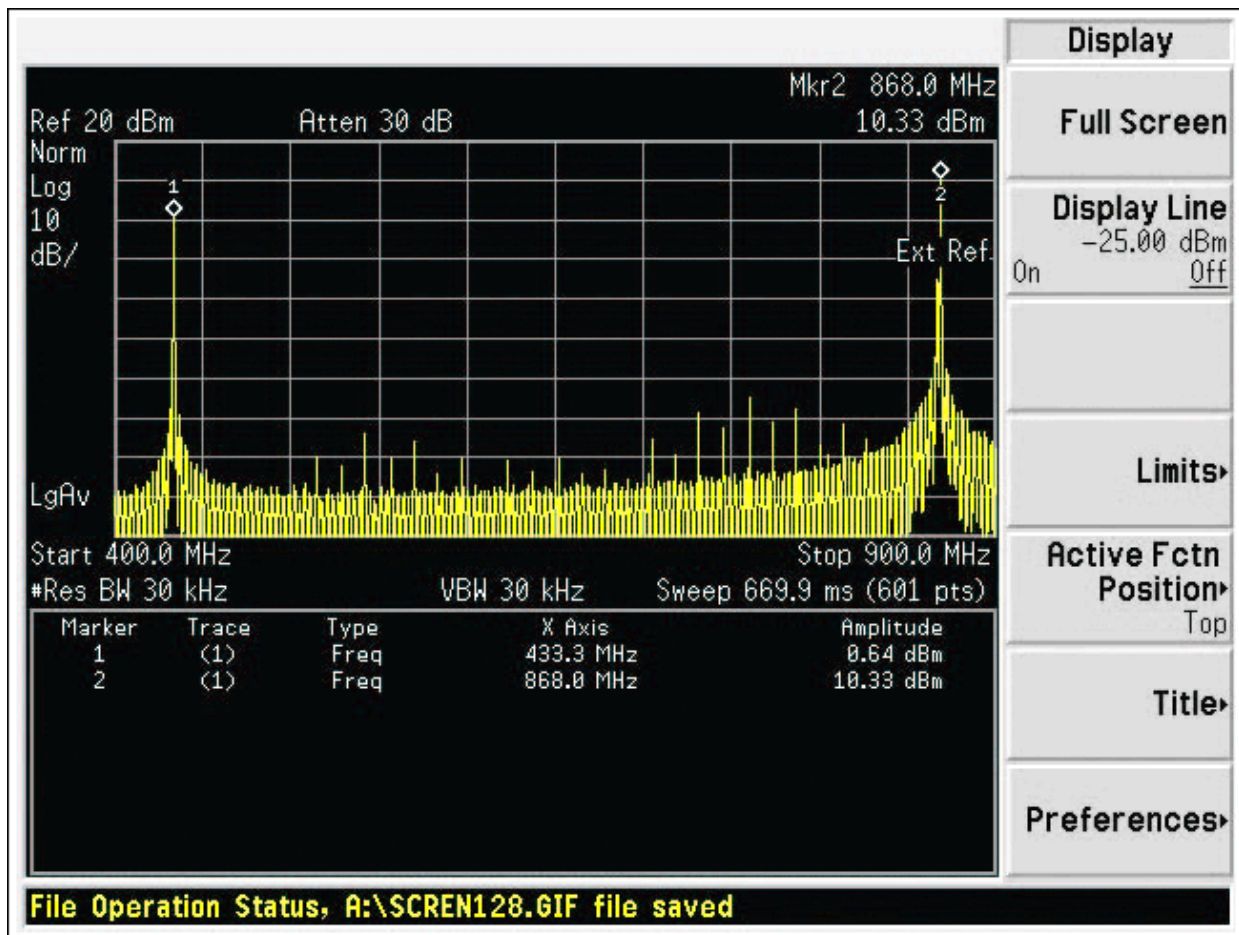The 868MHz radiated efficiency = 30.4%

Figure 7. Spectrum of the MAX7044EVKIT with 868MHz tank circuit and highpass L network.

The highpass L-network match attenuates the 434MHz component and significantly increases the efficiency of the desired 868MHz component to 30.5%. This demonstrates that an 868MHz signal with more than 10dBm of transmitted power into a 50Ω antenna can be produced with some simple changes to the existing matching network.

Summary of Simple Matching-Network Changes

The bias inductor to the MAX7044EVKIT was replaced with a smaller value that formed a resonant circuit with the combination IC and board capacitance at 868MHz. This made the 434MHz and 868MHz components equal in power. Replacing the harmonic filter with a simple highpass L-matching network improves the 868MHz-to-434MHz component by another 9dB, so that 868MHz is the dominant transmitted frequency. There is a small loss in power efficiency, but this circuit is still transmitting an 868MHz signal at more than 10dBm. There are more circuit changes that can be made to further enhance the 868MHz component with respect to the fundamental 434MHz frequency and its higher harmonics.

Suggestions for Future Work

These simple changes prove that external components can be modified to significantly enlarge the second harmonic power of a transmitter IC (compared to the fundamental frequency) while maintaining a high transmitted signal level. This is a good start, but more obstacles need to be overcome in order to transmit a signal that complies with operating regulations in the license-free bands of 868MHz in Europe and 915MHz in the U.S.

Additional Enhancement of the 868MHz Component

Enhancement of the 868MHz component is improved by increasing the Q of the resonant circuit, formed by the bias inductor and the capacitance to ground of the PA. This can be done by adding a capacitor to ground at the PA output pin and reducing the bias inductor. In this investigation, the bias inductor was reduced to 16nH to resonate with the stray capacitance on the board and in the IC. The inductor can be reduced to the 5nH to 10nH range and the total shunt capacitance increased to about 6pF, before the unloaded Q of the individual components significantly decreases the overall efficiency.

The highpass L-matching network's 434MHz rejection can be improved by simply adding a shunt inductor in the C6 position of Figure 6 to form a highpass pi network and by adjusting the inductor values. Careful selection of the three pi-network components should increase the total rejection of the 434MHz component to 25dB or 30dB. This is still short of the 46dB rejection needed to satisfy the ETSI requirement that all spurious emissions be below -36dBm, if the 868MHz transmitted signal is +10dBm. There are more suggested methods for improving the rejection toward the end of this application note.

Maintenance of Transmitter Efficiency

The modifications made thus far concentrate on enhancing the 868MHz component and rejecting the 434MHz component. These changes reduce the PA efficiency from nearly 50% for a 434MHz transmission to about 30% for an 868MHz transmission. However, further attempts to reject the 434MHz signal may degrade efficiency even more. Early measurements in the development of matching networks for 434MHz transmissions showed that the DC-current drain increased when the 434MHz matching network was mistuned. Given that a typical filter rejects frequencies by presenting a poor match at those frequencies, it is surprising that the current drain in these tests did not increase more. How can the rejection of 434MHz be further enhanced without causing more increases in DC current and consequent decreases in efficiency?

The Diplexer Approach

A diplexer is normally used in dual-channel receiver systems to connect a common receive antenna to two receivers, each tuned to a different frequency. The diplexer forms a good match to the antenna at both of the two design frequencies. If the receive antenna is replaced by the PA, there is now a separate path for the 434MHz component and the 868MHz component. The 868MHz path connects to a transmitting antenna and the 434MHz path connects to a resistive load on the circuit board. The advantage of this configuration over a simple 868MHz filter is twofold: the 434MHz component is matched (thus keeping the current drain low), and it is also sent to a load that does not radiate. If the antenna on the 868MHz port is correctly matched and tuned, the rejection of the radiated 434MHz component will be very strong. To further reduce the supply current at 434MHz, the diplexer concept could be modified to present higher impedance to the 434MHz component than to the 868MHz component.

There is a potential flaw with this approach—it assumes a linear signal source with a 50Ω load. The PA, which has a switched amplifier output, does not fit any linear models.

Revisiting the Switched-Amplifier Model

The spectrum in Figure 1 is based on the unfiltered output of the PA, which is a 25% duty-cycle square wave at 434MHz. The PA output is a short circuit for 25% of the 434MHz period. When the matching network is properly tuned, the short circuit occurs at the lowest point of a 434MHz sine wave. This is designed so the current "pumped into" the resonant circuit occurs at the minimum voltage (close to 0V or ground). The PA's predicted behavior is based on the circuit model of this switching waveform, which is connected to a resonant circuit with a resistive load. However, the model needs to be modified to have the resonant circuit at 868MHz. It may show that the 434MHz component is rejected by the 868MHz circuit without a large increase in supply current. This can explain why the current-drain measurements increased more when the matching network was mistuned from 434MHz. (Measurements increased by 10% to 20%, compared to the measurements in the 868MHz matching-network experiments.) Perhaps there is a local-current minimum at the second harmonic of 434MHz?

Reducing the Phase Noise

The ETSI requirement that all spurious transmissions be below an absolute power level of -36dBm imposes a restriction not only on the harmonic radiation, but also on the phase noise of the transmitter. In Europe, the 434MHz license-free band is between 433.05MHz and 434.79MHz. (The band's center is 433.92MHz, which explains why this particular frequency is widely used.) Outside the band edges, no radiation can be higher than -36dBm. At the edges, the MAX7044's largest contributor is the phase noise of the carrier frequency. The MAX7044's phase-noise density is specified at -92dBc/Hz, where "dBc" stands for "dB below the carrier."

According to ETSI requirements, the spurious power needs to be measured in a 100kHz bandwidth using a quasi-peak detector, which produces the same power measurement on the phase-noise waveform as an average power detector. Adding 50dB for the logarithmic ratio between the 100kHz measurement bandwidth and the 1Hz bandwidth in the density specification brings the measured power in a 100kHz bandwidth up to -42dBc. If the measured power is restricted to -36dBm, the MAX7044 can transmit +6dBm (max) at 434MHz in Europe.

In the 868MHz to 870MHz frequency range, the widest allowable band is 868.0MHz to 868.6MHz. Transmitters cannot radiate more than -36dBm of average power outside of this band. The power outside the band is measured in a 100kHz bandwidth, as it is at 434MHz, but the band is now 600kHz instead of 1.74MHz. This is a restriction almost 3 times as narrow at 868MHz than at 434MHz. In addition, the second harmonic of 434MHz—which is 868MHz—has a phase-noise density that increases as the square of the frequency. This means that it will be 6dB higher at 868MHz than it is at 434MHz. The phase-noise density of a 434MHz carrier transmitted from the MAX7044 is approximately -89dBc/Hz at 300kHz from the carrier and -83dBc/Hz at 868MHz. In a 100kHz bandwidth, the average power at 300kHz is $[-83 + (10\log_{10}(100kHz))] = -33dBc$. This restricts the MAX7044's transmitted power at 868MHz to below -3dBm.

The MAX7044 oscillator's relatively high phase-noise density results from a design that allows the VCO frequency inside the device to be tuned from 300MHz to 450MHz. This phase-noise density is acceptable in the U.S. license-free band of 260MHz to 470MHz, because the spurious-radiation requirements at frequencies near the carrier frequency are not nearly as restrictive as they are in Europe. In order to transmit at power levels near +10dBm in the European 868MHz band the VCO in the MAX7044 needs to change to a more narrowband and lower phase-noise architecture, like an L-C oscillator.

Conclusions

With simple changes to the matching network, it is possible to make a 434MHz switched-amplifier transmitter radiate more power at 868MHz than at 434MHz. This article discussed how a MAX7044EVKIT with an 868MHz tank circuit and highpass L-impedance transformation produced an 868MHz carrier at +11dBm. In this situation, the 868MHz carrier was nearly 9dB higher in power than the 434MHz fundamental frequency. The PA efficiency at 868MHz was 30%.

More rejection of 434MHz is needed to satisfy U.S. and European spurious radiation limits. However, different topologies and modeling approaches can improve rejection of the 434MHz component. An adaptation of the classic diplexer routes the 868MHz component to the antenna and the 434MHz component into a dummy load.

A change in the tuning circuit in the switched-amplifier model leads to an improved selection of the 868MHz matching network. The VCO can be modified to produce lower phase-noise density, in order to satisfy the ETSI spurious-radiation limits in the 868MHz band.

Related Parts		
MAX7044	300MHz to 450MHz High-Efficiency, Crystal-Based +13dBm ASK Transmitter	Free Samples

MAX7044EVKIT	Evaluation Kit for the MAX7044	
MAX7060	280MHz to 450MHz Programmable ASK/FSK Transmitter	Free Samples

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