

LOW POWER RADIO TRANSMITTER

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Abstract – A transmitter consisting of a voltage controlled oscillator (VCO) and power amplifier (PA) for the 400 MHz Medical Implanted Communication System band (MICS) was built in a standard 0.35- μm CMOS process. A push pull architecture was used for both the VCO and the PA. Two off-chip inductors were needed.

The design was optimized for 400 μW output power at 3 V supply, which resulted in an efficiency of 26 %. This gives a total power consumption of 1.6 mW, of which the VCO uses about 0.3 mW.

I Introduction

Today the communication with medical implanted devices take place by inductive coupling. The drawback with this system is low bandwidth. To increase the data rate radio communication can be used.

In the new European Telecommunication Standard Institute (ETSI) standard for the MICS-band [1] at 400 MHz, it is stated that the maximum emission bandwidth for a session is 300 kHz, which gives room for at least ten simultaneous sessions in the band. A session includes all the devices, which are necessary to complete the communication task. The bandwidth is defined to be between the points where the signal is down by 20 dB. The maximum output power allowed to leave the human body is 25 μW . The reason for this low figure is that the frequency band is shared with weather balloons. There are also restrictions of how much leakage that is permitted to other frequency bands, see table 1.

The battery in the pacemaker shall last for about ten years, which puts high energy restrictions on all the components in the pacemaker, and creates a major challenge for radio transceiver design.

Mode	47 - 74 MHz 87.5 - 118 MHz 174 - 230 MHz 470 - 862 MHz	Other frequencies below 1000 MHz	Frequencies above 1000 MHz
Operating	-54 dBm	-36 dBm	-30 dBm
Standby	-57 dBm	-57 dBm	-47 dBm

Table 1: Permitted leakage.

II DESIGN

The building blocks of the transmitter are a VCO, a PA, and an impedance transforming network. The transmitter can generate a Frequency Shift Key (FSK) signal. The purpose of the impedance transforming network is to transform the antenna impedance of 50 Ω to the impedance wanted at the output of the PA. A high efficiency combined with a low output power requires the antenna impedance to be transformed up. An efficient impedance transformation is possible with high quality off-chip inductors.

A Inductors

The requirement of low power and the low operating frequency indicate that the inductors have to be off-chip. An inductor from Coilcraft called 0603CS-R18 [2] was chosen for the oscillator resonance tank. This is a surface mounted inductor with a spice model according to figure 1. The quality factor (Q) is equal to 23 at 400 MHz. For the impedance transforming network Coilcraft 0603CS-R12 was chosen. The parameters for this inductor are:

$$R_1 = 26 \Omega, \quad R_2 = 10 \text{ m}\Omega, \quad R_{\text{var}} = k\sqrt{f} \Omega$$

$$k = 2.70 \cdot 10^4 \frac{\Omega}{\sqrt{\text{Hz}}}, \quad C = 63 \text{ fF}, \quad L = 119 \text{ nH}$$

which gives a Q-value of 32 at 400 MHz. The physical size of these inductors is 1.8 \times 1.12 \times 1.02 mm.

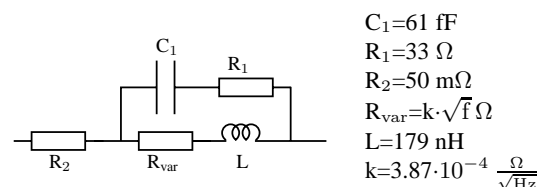


Figure 1: Spice model of the inductor, 0603CS-R18.

B Oscillator

The design is shown in figure 2 below. This oscillator is designed so that N- and P-transistors have equal g_m . The number of transistor fingers is adjusted so

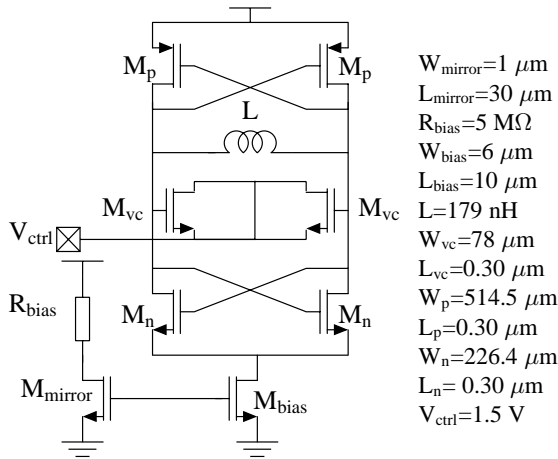


Figure 2: Schematic of the VCO with PMOS and NMOS as active devices, W_{bias} given for loop gain equal to two.

that the width of each gate is approximately $20 \mu\text{m}$, to reduce the gate resistance. The size of the MOS varactor, M_{vc} , is chosen so that the frequency is in the range 398-409 MHz when V_{ctrl} is between 0-3 V.

When R_{bias} is equal to $5 \text{M}\Omega$ the start up loop gain is equal to two and the phase noise is -108dBc/Hz at 150kHz offset.

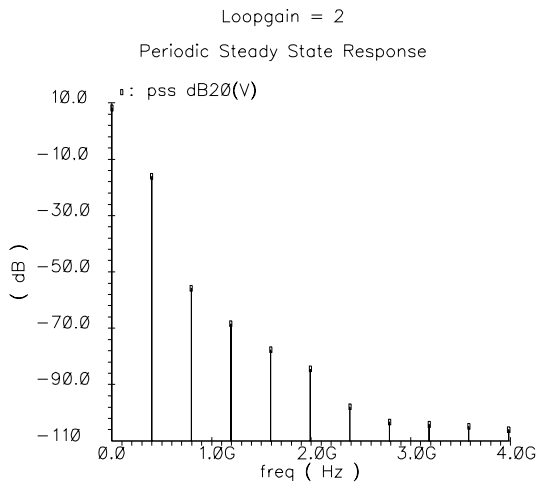


Figure 3: Harmonics of the oscillator.

The leakage to other frequencies is caused mainly by the harmonics. A PSS-analysis with SpectreRF was performed and the result is plotted in figure 3. The second harmonic is strongest and it is down by 40 dB relative the fundamental.

To achieve a symmetrical VCO load the input capacitance of the single ended power amplifier has to be calculated and added to the unloaded branch of the differential VCO. Then one must make sure that the oscillator has a wide enough tuning-range. In [4]

it is described how high performance switched tuning can be achieved for a differential oscillator. That method is used here, figure 4. Three bits tuning were used and it achieved 15 % tuning-range.

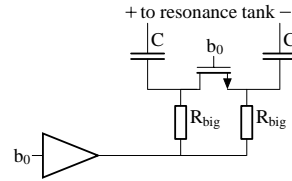
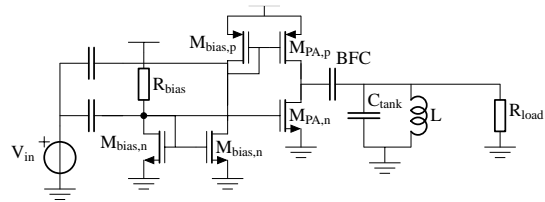


Figure 4: Part of tuning circuit.

C PA push-pull

A schematic of the design can be seen in figure 5. The idea is that the P- and N- transistors act as switches controlled by the oscillator signal. If the bias is not too high they will not be on at the same time. The capacitance in the resonance tank must be reduced to compensate for the parasitics in the transistors. The resonance tank at the output is replaced by the impedance transforming network in the final circuit.



$W_{\text{PA,n}}=60 \mu\text{m}$, $W_{\text{PA,p}}=90 \mu\text{m}$, $L_{\text{tran}}=0.30 \mu\text{m}$, $V_{\text{dd}}=3\text{V}$,
 $R_{\text{bias}}=900 \text{k}\Omega$, $V_{\text{in}}=780 \text{mV}$, $C=805.5 \text{fF}$, $W_{\text{bias,n}}=0.60 \mu\text{m}$,
 $W_{\text{bias,p}}=1.60 \mu\text{m}$, $L_{\text{bias}}=0.30 \mu\text{m}$, $\text{BFC}=2 \text{pF}$, $R_{\text{t}}=2.5 \text{k}\Omega$

Figure 5: Push pull power amplifier.

The amplifier is optimized for $400 \mu\text{W}$ output power. When the bias resistance is changed also the output power changes, the result is plotted in figure 6. As expected the efficiency decreases with the output power. The output power can be changed from $400 \mu\text{W}$ down to $200 \mu\text{W}$ when R_{bias} is changed from 0.9 to $3.0 \text{M}\Omega$. When the control resistance is $0.9 \text{M}\Omega$ the output power is $400 \mu\text{W}$ and the efficiency is 34 %. The peak output voltage is then 1.4V .

D Impedance transforming network

The antenna impedance, R_{s} , is 50Ω and the load impedance needed by the amplifier, R_{load} , is $2.5 \text{k}\Omega$. The impedance must thus be transformed up 50 times. The transforming network will be connected to the output of the amplifier. This makes an L-match attractive since the output capacitance can then be ab-

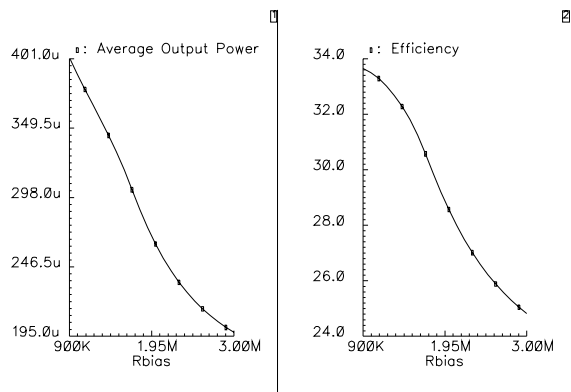


Figure 6: Efficiency and output power vs. R_{bias} .

sorbed in the matching network. Furthermore the L-match contains a minimum number of components and is very robust. The equations and the values in this case are given in equation (1), according to [3].

$$\begin{aligned} Q &= \sqrt{\frac{R_1}{R_s} - 1} = 7.0, \quad L = \frac{QR_s}{\omega_0} = 138 \text{ nH} \\ C &= \frac{Q}{\omega_0 R_1} = 1.10 \text{ pF} \end{aligned} \quad (1)$$

The impedance transforming network was added to the output of the amplifier and the resonance tank was removed. A simulation of output power and efficiency versus R_{bias} , and a PSS-analysis of the harmonics were done. The efficiency was 2 % lower than without the impedance transforming network. The worst leakage was at the second harmonic and it was down by 46 dB relative the fundamental, which is sufficient, see section E.

E Radio transmitter

The transmitter has a start up signal, called Power Up, which turns on the supply voltage to the transmitter. This signal also injects a pulse to the oscillator through the PA, which guarantees a quick start up, simulated to approximately 10 ns.

Simulations of the full transmitter were done to see if the demands were fulfilled.

The leakage at the output of the transmitter was simulated with SpectreRF and plotted, figure 7. This figure should be compared with table 1, where the allowed leakage is specified. To do this one must compensate for the attenuation in the human body at the relevant frequencies. The attenuation in the body depends on the thickness of the skin and fat, and how deep into the muscles the antenna is buried. For the values below the antenna is buried at a depth of 3.0 cm, which is a good approximation for an antenna close to the pacemaker.

For 0.5 cm skin and 1.0 cm fat the attenuation at 800 MHz is 14 dB and it rapidly increases for the

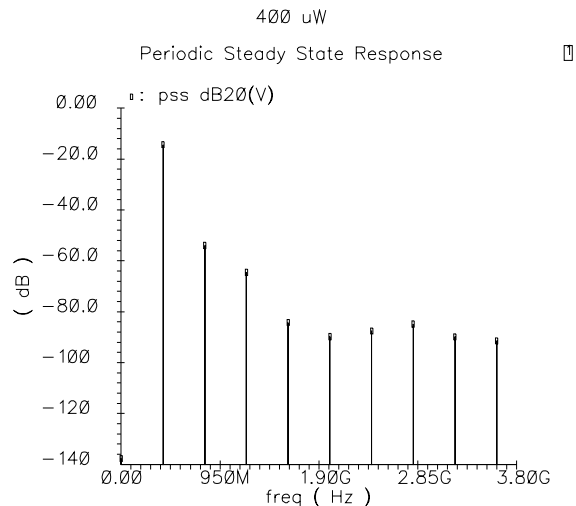


Figure 7: Leakage of the radio transmitter.

other harmonics, according to [5]. The harmonic to worry about is thus the second since it is not attenuated so much in the body and the demands are highest in that frequency range.

For 400 μW (= -4 dBm) output power the second harmonic shall be down by at least 36 dB (54-14-4) relative the fundamental. In figure 7 the second harmonic is down by 40 dB, providing some margin.

The efficiency and output power vs. bias level was simulated. The output power can be controlled between 400 μW and 280 μW by changing R_{bias} between 0.9 M Ω and 3 M Ω . The efficiency for the whole transmitter varies from 26 %-20 % when R_{bias} is in this range. The total power consumption is 1.5 mW.

III LAYOUT

Due to the low power consumption required, the off-chip inductor of the VCO resonance tank must have a high inductance. This makes the design sensitive to parasitic capacitance.

When drawing the layout it is impossible to avoid intersections between metal layers and the associated parasitic capacitance. After eliminating as much of the intersection area as possible about 300 fF remained from the resonating nodes to signal ground, that is 150 fF on each side.

The pads are made in metal three (top metal) with a ground shield in metal one beneath it. The shield reduces the loss due to substrate currents but adds some capacitance. The pads have a capacitance of approximately 250 fF to ground. All this parasitic capacitance forces the designer to reduce the intentional capacitance in the tank to keep the wanted resonance frequency. If the tuning-range then is insuffi-

cient to compensate for process variations, a smaller inductance must be chosen, resulting in an increased power consumption.

The packaging will also influence the behaviour of the circuit, so it is important that one chooses a good package and simulates with those parasitics as well.

The size of the chip is $1020 \mu\text{m} \times 650 \mu\text{m}$ including pads and $350 \mu\text{m} \times 200 \mu\text{m}$ excluding.

A Simulation of layout

The simulations previously made for the schematic was also done for the layout (post-layout simulation). The leakage was simulated with SpectreRF and the results can be seen in figure 8. The phase noise was

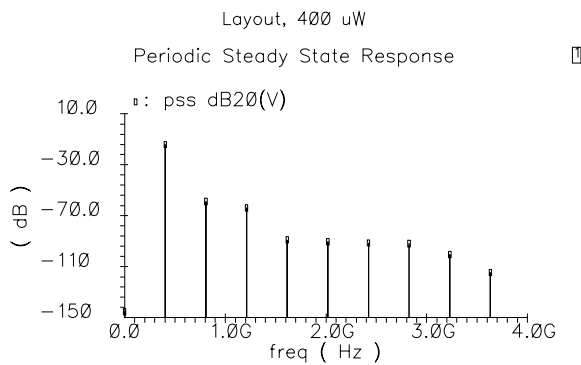


Figure 8: Harmonics of transmitter (post-layout).

simulated to -93 dBc/Hz at 150 kHz offset. The output power of the second harmonic shall be down by 36 dB relative to the fundamental, according to section E, and in figure 8 it is down by 44 dB.

Also the output power and efficiency were simulated and plotted vs. R_{bias} , see figure 9. The output power can be changed from $410 \mu\text{W}$ to $113 \mu\text{W}$ when R_{bias} is changed from $800 \text{ k}\Omega$ to $3 \text{ M}\Omega$ and the efficiency is then between 26 % and 9.0 % with a power consumption of 1.6 mW.

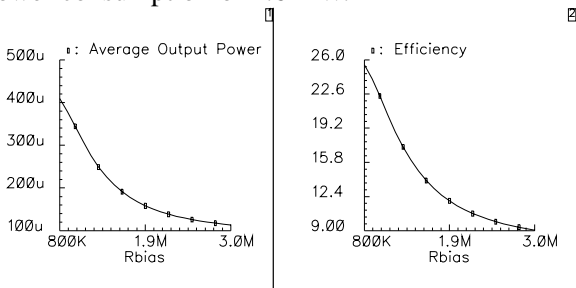


Figure 9: Power and efficiency of transmitter (post-layout).

The influence of supply voltage variations on oscillation voltage, output power and efficiency was also investigated. The oscillation is expected to start

first when the supply voltage is slightly above 2 V, because there are four transistors stacked in the oscillator, two as negative resistance, one for the tail current source, and one to turn the power supply on and off. The oscillator starts when the supply voltage is 2.3 V, see figure 10.

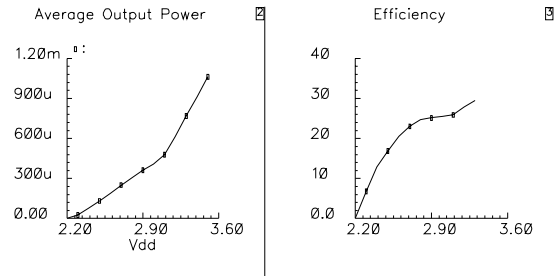


Figure 10: Effects of different V_{dd} .

IV CONCLUSIONS

A low power radio transmitter is presented, which satisfy the ETSI requirements of the MICS frequency band. The circuit was made in a standard $0.35\text{-}\mu\text{m}$ CMOS process with two external inductors. The output power is $400 \mu\text{W}$ with an efficiency of 26 %. This gives a total power consumption of 1.6 mW.

Due to the switched tuning and the varicap it is necessary to use a combined analog and digital phase locked loop to control the transmitter frequency.

Acknowledgements

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