FSK Coherent Demodulation Using Second-Harmonic Injection Locked Oscillator

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Abstract—We present an alternative coherent demodulation of frequency shift keying (FSK) signals based on the use of a super-harmonic injection locked oscillator (ILO). Demodulation consists of multiplying the incoming FSK signal by the output of the ILO using an up-conversion mixer. The product includes a second harmonic signal that locks the oscillator, closing a non-linear feedback loop, and synchronizes its output with the incoming FSK signal. In addition to the second harmonic, the product also includes a base band signal that reproduces the original modulation. We built and tested a hybrid prototype of the demodulation system for the frequency range from 250 to 300 MHz. The circuit consists of a second-harmonic differential output ILO with varactor diodes as tuning elements and a four quadrant analog multiplier. Our results demonstrate the reliability and robustness of the demodulator system.

Index Terms—Frequency shift keying (FSK) demodulator, injection locked oscillators (ILOs), synchronization.

I. INTRODUCTION

Frequency shift keying (FSK) is a form of digital modulation that is widely used in wireless communications. FSK signals are usually demodulated by means of FM to AM conversion using frequency discriminators or quadrature demodulators. In both cases demodulation of the FM signal is non-coherent. Coherent demodulation of FM signals can also be accomplished by using phase locked loop (PLL) systems.

Recently, an injection locked demodulator with no external components was reported [1], [2]. This system performs a coherent demodulation of FSK signals by synchronizing the output of a non-sinusoidal oscillator with the input signal at the fundamental frequency.

Here we present an alternative procedure for coherently demodulating FSK signals using injection locking of an L-C voltage controlled oscillator at the second harmonic through a non linear feedback loop. Increased robustness and simplicity as well as improved AM noise rejection are the main advantages of the proposed system, compared to previous approaches.

II. CIRCUIT FUNDAMENTALS

Injection is a common way to synchronize an oscillator with an incident signal. When the injected signal is close to a harmonic of the oscillator free running frequency, the ensemble is known as a super-harmonic injection locked oscillator (SH-ILO) [3]. Since injection efficiency decreases with the harmonic order, most studies of SH-ILOs are carried out using injection at the second harmonic. Second harmonic ILOs (second-h-ILOs) have been used previously for direct analog quadrature generation [4], phase shifting [5] and coherent BPSK signal demodulation [6], [7].

Fig. 1 shows a second-h-ILO implementation. The circuit is a cross coupled-pair oscillator, whose resonant tank consists of a double inverter transformer and a couple of varactors. The primary of the transformer acts as the inductive element of the resonant tank, while the secondary acts as the coupling element for sensing the differential output of the oscillator. The varactor diodes also play a double role: first by providing the capacitance for locking, both windings of the transformer have a center tap. The one in the primary is used to inject the input signal and to bias the transistor cross pair. The one in the secondary is grounded for these signals:

\[
\begin{align*}
V_1 &= A_1 \sin(2 \pi f t + \phi(t)) \\
V_2 &= A_2 \sin(4 \pi f t + \psi)
\end{align*}
\]

(1)

where, \(A_1\) and, \(A_2\) are their amplitudes, \(\phi(t)\) and, \(\psi\) the corresponding phases and, \(f_1\), the locking frequency. Note that, \(\phi(t)\), takes into account the dynamics of the oscillator frequency, \(f(t) = f_1 + \frac{d\phi(t)}{dt}\).

Due to the non-linear behavior of the varactor diodes, the injected signal, \(V_1\), at twice the locking frequency mixes with the oscillator signal at frequency \(f(t)\). As a consequence, the capacitance of the varactor diodes at the fundamental frequency changes. This change is reflected in \(\phi(t)\) and then in \(f(t)\). Equilibrium is reached when \(\frac{d\phi(t)}{dt} = 0\) and the final frequency
of the oscillator will be the locking frequency, \( f_L \), [5], [6]. Under locking conditions there are two possible steady-state values for the phase of the oscillator output voltage, \( \phi_{ss} \):

\[
\phi_{ss} = \frac{\psi + \theta_{ss}}{2} \quad \text{or} \quad \phi_{ss} = \frac{\psi + \theta_{ss}}{2} + \pi
\]  

(2)

where \( \theta_{ss} \) is given by:

\[
\theta_{ss} = \arcsin \left( \frac{2C_{DC} \frac{f_r^2 - f_f^2}{\alpha A_2}}{\frac{f_r^2}{f_f^2}} \right)
\]  

(3)

being, \( f_r \), the free running frequency of the oscillator and, \( C_{DC} \), and, \( \alpha \), the capacitance of the varactors and its derivative with respect to the applied voltage, respectively, both at the bias point \( V_{DC} \).

Fig. 2 is a circuit diagram of the proposed FSK demodulator. In this circuit, the mixer acts as an analog multiplier and the second-h-ILO could be that shown in Fig. 1.

In order to understand the demodulation process, let us assume that, \( V_{ref} \), is a continuous wave signal whose frequency is, \( f_L \), and whose arbitrary phase is chosen so that:

\[
V_{ref} = A_{ref} \cos(2\pi f_L t)
\]  

(4)

in steady-state:

\[
V_1 = A_1 \sin(2\pi f_L t + \Phi_{ss})
\]  

(5)

and the injected signal, \( V_{inj} \), (which is equal to the product of \( V_{ref} \) and \( V_1 \)) can be written as:

\[
V_{inj} = \frac{A_1 A_{ref}}{2} \sin(\Phi_{ss}) + \frac{A_1 A_{ref}}{2} \sin(4\pi f_L t + \Phi_{ss})
\]  

(6)

According to (6), there are two components in the injected signal, \( V_{inj} \): a base band component, \( V_0 \), and a second-harmonic component, \( V_2 \). By comparing \( V_2 \) in (6) with \( V_2 \) in (1), it is straightforward to see that for the block diagram in Fig. 2, \( \psi = \Phi_{ss} \) and \( A_2 = A_1 A_{ref}/2 \). By substituting these conditions in (2) and using expression (3) for \( \theta_{ss} \), the base band component in (6), \( V_0 \), can be rewritten as:

\[
V_0 = \frac{A_1 A_{ref}}{2} \sin(\theta_{ss}) = \frac{2C_{DC} f_r^2 - f_f^2}{\alpha} \frac{f_r^2}{f_f^2}
\]  

(7)

where we have taken into account that the varactor diodes in Fig. 1 are reverse biased, and then, \( \alpha < 0 \).

From (7) we can see that at resonance (i.e., when \( f_L = f_r \)), the base band signal is equal to zero. Any change in the locking frequency will be reflected in a change of the base band signal, \( V_0 \), which could be positive or negative depending on the frequency shift. According to this, if the signal, \( V_{ref} \), is a FSK signal the resulting base band component, \( V_0 \), will reproduce the original modulation. We have to remark that \( V_0 \) does not depend on the amplitude of the reference signal, \( V_{ref} \), provided it is great enough to ensure locking. This implies that, ideally, there is a perfect rejection of AM noise using the FSK demodulator shown in Fig. 2.

III. CIRCUIT DESIGN AND CONSTRUCTION

We designed and built a hybrid version of the FSK demodulator using a second-h-ILO circuit. Fig. 3 is a photograph of the printed circuit board.

Transformers were printed directly onto the board as interleaved square spirals. Wedge bonding bridges were used to interconnect the different parts of these components. Electromagnetic simulation tools were used to optimize the geometry of the passive components in order to achieve good performance in both common and differential modes of operation in the frequency range of interest (i.e., 250–300 MHz). The mixer used in this circuit is an ADEX-10L from Mini-Circuits®. The cross pair was implemented using a couple of transistors, AT-32033, from Agilent Technologies. Non-linear tuning of the circuit was achieved using a couple of BB-833 varactors from Infineon Technologies. The circuit consumption is 2 mA when biased with a 1.5 volts battery.

IV. ELECTRICAL CHARACTERIZATION

To evaluate the steady-state response of the hybrid FSK demodulator shown in Fig. 3, we used a continuous wave reference signal, \( V_{ref} \). The circuit was biased at \( V_{DC} = 1.5 \text{ V} \) and \( V_{var} = 0 \text{ V} \), resulting in a free-running frequency of 286.10 MHz. The power of the reference signal was set to \(-3,-4,-5\) dBm. These power levels ensure locking of the ILO in a frequency range of about 700, 500, and 400 kHz around its free-running frequency, respectively. Fig. 4 shows the frequency-to-voltage transfer function of the FSK demodulator, under these biasing conditions. This function is weakly on the input power level for frequency shifts above \(-200\) kHz. For frequency shifts below this value substantially the same frequency-to-voltage transfer
Fig. 4. Steady-state frequency-to-voltage transfer function of the hybrid FSK demodulator for three input power levels: (—) \(-3\) dBm, (— — —) \(-4\) dBm and (— — —) \(-5\) dBm.

Fig. 5. AM rejection of the hybrid FSK demodulator for an input power level of \(-4\) dBm. Triangles, squares and circles correspond to 10%, 20% and 30% amplitude modulation depths of the input signal.

Fig. 6. Output response of the hybrid FSK demodulator to FSK signals. The input frequency is shifted every 500 \(\mu s\) (upper plot) or 1 ms (lower plot).

function is observed, regardless the input power level. For frequency shifts from about \(-100\) kHz to \(-100\) kHz, an almost linear behavior is observed in all the curves. Eventually, this will allow the demodulation of FM signals in addition to FSK signals.

We also studied the AM rejection of the FSK hybrid demodulator. Fig. 5 shows the AM demodulation gain as a function of the frequency shift when the input signal is amplitude modulated with a single sinusoidal tone at 1 kHz. The input power is set to \(-4\) dBm. Modulation depths of 10%, 20% and 30% have been used in order to obtain a measurable signal at the output of the demodulator for all frequency shifts. Measured AM rejection is always better that 30 dB.

Finally, Fig. 6 shows the response of the hybrid demodulator to a FSK signal. The input power is \(-4\) dBm. Two rectangular waveforms were used to switch the carrier frequency from 285.85 MHz to 286.15 MHz every 500 \(\mu s\) or 1 ms, respectively.

V. CONCLUSION

We studied coherent demodulation of FSK signals using a second-h-ILO with non-linear feedback through a mixer. Based on this study we propose a new demodulation circuit. After a detailed analysis of the phase dynamics of the proposed circuit, we derive a compact relationship between the frequency shift of the input signal and the output base band voltage. We designed, built and tested a printed circuit board hybrid prototype. We studied the frequency-to-voltage transfer function of the demodulator, as well as its AM rejection. Finally, the circuit prototype was successfully used to demodulate FSK signals and recover the original modulation. Further work is under way to implement an integrated version of the circuit, working in the ISM 2.45 GHz frequency band.

REFERENCES