THE INJECTION-LOCKED-OSCILLATOR AS A MICROWAVE AMPLIFIER OF MSK MODULATED SIGNALS

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ABSTRACT

The use of an injection-locked-oscillator (ILO) as a microwave amplifier of minimum-shift-keying type of digitally modulated signal has been described. A large signal model of the ILO which identifies the key circuit parameters has been derived. Both the theoretical and experimental results in the form of the spectral spreading effect of a 6 GHz IMPATT microstrip ILO on the filtered 5 M bits/sec MSK signal have been presented. These results have been obtained for various values of the gain and the frequency offset.

I. Introduction

The application and analysis of injection-locked-oscillators as microwave amplifiers of the analog angle modulated signals is well known[1,2]. The properties of injection-locked-oscillators as microwave amplifiers of digital angle modulated signals (e.g., PSK, FSK) has been reported by Kuno[3] and Paik-et-al[4]. Kuno concluded that the required locking bandwidth of the ILO is determined by the transient phenomena at the phase transients which occur at the interbit switching instants. In practice a locking bandwidth equal to four to five times the bit rate may be required. Paik[4] however measured the bit error rate of an ILO having such a bandwidth when amplifying a QPSK modulated signal and observed an anomalous effect. The bit error rate at high E_b/N_o ratio did not decrease rapidly in the expected fashion, and the ILO introduced an error floor (Fig. 11 in Ref. 4). He suggested that this might be due to 180° phase discontinuities resulting in large amplitude modulation of the carrier. Long term frequency instability was another reason mentioned to explain this behaviour. Though their test set up did not include an IF filter, in practical transmitters, the digitally modulated signal is filtered at IF to limit the spectrum before upconversion and microwave amplification. The narrow band filtering would result in the envelope of the modulated signal going to zero at the instants of 180° phase shifts. This may result in the unlocking of the ILO type microwave amplifier; thus further degrading the bit-error-rate performance.

Minimum shift keying (MSK) is a digital modulation technique which may be treated equivalently as offset keyed QPSK with sinusoidal symbols, or as a continuous phase FSK. The basic modulation process consists of linearly varying the phase of the carrier by 90° over a bit interval. The phase is advanced for a mark and retarded for a space. In addition the phase continuity of the carrier is maintained at the interbit switching instants. Thus MSK is free of phase transients and therefore the envelope of the filtered MSK signal does not go to zero and the amplitude modulation as a result of filtering is minimal[5]. This suggests that an ILO should be capable of high gain amplification of MSK signals. Filtering of the modulated signal in the transmitter, however, will cause some amplitude modulation of the MSK signal. If an ILO is used to amplify the filtered signal, the phase and amplitude nonlinearities and AM/PM conversion effects will cause some degradation in the bit error performance and spreading of the filtered spectrum.

A model of ILO which identifies the key circuit parameters and which is capable of describing the effects of phase and amplitude nonlinearities is presented in Section II. The theoretical and experimental results for a 6 GHz ILO amplifier with 5 M bits/sec filtered MSK signal as the input are included in Section III.

II. The ILO Model

Adler's equation for large signal injection locking is given by[6]

$$\frac{d\alpha}{dt} = \Delta\omega_o - \frac{E_i}{E_o}\frac{\omega_o}{2Q}\,\frac{\sin\alpha}{1 + \frac{E_i}{E_o}\cos\alpha} + \phi_i'(t) \qquad (1)$$

where the input signal is given by

$$e_i = E_i \cos(\omega_i t + \phi_i(t))$$

and the output signal of the locked oscillator by

$$e_o = E_o \cos(\omega_i t + \phi_i(t) + \alpha(t))$$

$\Delta\omega_o$ = Frequency Offset = $\omega_i - \omega_o$

ω_o = Free-running frequency of the ILO

Q = External Q of the oscillator.

Assuming $\frac{E_i}{E_o} < 1$, $\sin\alpha \simeq \alpha - \frac{\alpha^3}{6}$ and $\cos\alpha = 1 - \frac{\alpha^2}{2}$

Equation (1) may be expressed as

$$\frac{d\alpha}{dt} = \Delta\omega_o - \frac{E_i}{E_o}\left(1 - \frac{E_i}{E_o}\right)\frac{\omega_o\alpha}{2Q} + \frac{E_i}{E_o}\frac{\omega_o}{2Q}\left(1 - \frac{4E_i}{E_o}\right)\frac{\alpha^3}{6} + \phi_i'(t) \qquad (2)$$

By applying an iterative technique, the following approximate solution is obtained for this equation:

$$\alpha(t) = \phi_o + k_1\phi_i'(t) + k_2(\phi_i'(t))^2 + k_3(\phi_i'(t))^3 \qquad (3)$$

where,

$$\phi_o = \frac{1}{\omega_{m'}}\left(\Delta\omega_o + \frac{\omega_{m''}\Delta\omega_o^3}{6\omega_{m'}^3}\right)$$

$$\omega_{m'} = \left(1 - \frac{E_i}{E_o}\right)\frac{E_i}{E_o}\frac{\omega_o}{2Q} \qquad \omega_{m''} = \left(1 - \frac{4E_i}{E_o}\right)\frac{E_i}{E_o}\frac{\omega_o}{2Q}$$

$$k_1 = \frac{1}{\omega_{m'}} + \frac{1}{2}\frac{\omega_{m''}\Delta\omega_o^2}{\omega_{m'}^4}$$

$$k_2 = \frac{1}{2}\frac{\omega_{m''}\Delta\omega_o}{\omega_{m'}^4} + \frac{1}{\omega_{m'}^2}\left(1 + \frac{1}{2}\frac{\omega_{m''}\Delta\omega_o^2}{\omega_{m'}^3}\right)$$

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$$k_3 = \frac{1}{6}\,\frac{\omega_m''}{\omega_m'^{\,4}}$$

Because both ω_m' and ω_m'' are functions of input signal amplitude E_i, AM/PM effect is included in (3) through them.

An expression for the change in the ILO output amplitude from the free-running condition may be obtained from Kurokawa's[7] expression for the variation in the output power:

$$\frac{\Delta P}{P_o} = 2\,\frac{P_i}{P_o}\left(\frac{2}{s} - 1\right)\cos\phi_o \qquad (4)$$

where

P_i = Measured input power to the locked oscillator

P_o = Output power of the free-running oscillator

ΔP = Output power variation on locking.

The factor s is a measure of the device negative resistance nonlinearity and is given by

$$s = \frac{1}{R_L}\,\frac{1}{I}\,\frac{\partial R}{\partial I}\bigg|_{I = I_o}$$

where

I = Amplitude of the RF current through the device negative resistance.

I_o = I for free-running oscillator.

R_L = Load Resistance

R = Magnitude of the device negative resistance.

From (4) using $P_i = \dfrac{E_i^2}{8R_L}$, $P_o = \dfrac{E_o'^2}{2R_L}$ and the output power of the locked oscillator as $P_{out} = P_o + \Delta P$. We may write

$$E_o = E_o'\left(1 + \frac{1}{2}\,\frac{E_i}{E_o'}\left(\frac{2}{s} - 1\right)\cos\phi_o\right) \qquad (5)$$

where E_o' represents the output signal amplitude of the free running oscillator.

Equations (3) and (5) may be used to find the output amplitude and phase. From these equations it is evident that the key circuit parameters which determine the phase, AM/PM and amplitude characteristics of the ILO are the following:

(i) The difference $\Delta\omega_o$ between the input carrier frequency and the free running frequency.

(ii) The external Q of the oscillator

(iii) The gain of the ILO defined as E'_o/E_i

(iv) The nonlinearity parameter s of the device.

III. Experimental and Theoretical Results

The performance of a 6 GHz microstrip ILO was evaluated experimentally and theoretically with a 5 M bits/sec input signal.

The Test Set-Up

The experimental test set-up used is shown in Fig. 1. The 5 M bits/sec, 60 MHz MSK signal was generated by differentially coding and demultiplexing the 5 M bits/sec data from the pseudorandom signal generator to form I and Q data channels. In the I-Q carrier generator block of Fig.1, a 60 MHz signal was processed with the clock signal to generate I and Q channel carriers as $\cos\omega_0 t \cos \pi t/T$ and $\sin \omega_0 t \sin \pi t/T$ (where ω_0= IF freq.=60 MHz; and 1/T=clock frequency). These quadrature carriers were then amplitude modulated with the I and Q channel data bits using double balanced mixers. The output of these mixers was summed to generate the 5 M bits/sec MSK signal at an IF frequency of 60 MHz. A 5th order Butterworth filter with a 3 dB bandwidth equal to 7.5 MHz was used as the IF filter. The MSK power spectra before and after filtering at IF and at the input to ILO is shown in Fig.2. The ILO output power spectrum was measured for various values of the gains and frequency off-sets and the results are shown in Fig.3.

Computer Simulation

Based on the model discussed in Section II a simplified computer simulation has been initially carried out to calculate the ILO output power spectrum. A 30 bits random data string was used as the input. The particular string selected was such that all the possible words occurred with nearly equal probability. A 512 point DFT, correlation and convolution were used in calculating the power spectra at various stages of the system. An experimentally determined external Q value of 40 was used in the simulation. The envelope of the computed spectra is shown by the dashed line in Fig.3.

IV. Discussion of Results and Conclusions

As may be seen from Fig.2, upconversion to 6 GHz and amplification prior to ILO caused very little spreading of the filtered spectrum. The experimental results indicate that the spectrum improved as the gain was increased in the range of 12-25 dB, but rapidly deteriorated as the corresponding locking bandwidth approach the input modulated signal bandwidth. Thus for a particular frequency off-set $\Delta\omega$, there appears to be an optimum gain which gives the least spreading of the spectrum. As may be seen from Fig. 3(c), the theoretical results for $\Delta\omega$ = 4MHz predict such a behaviour; however for lower values of $\Delta\omega$, the theoretical results do not agree with those obtained experimentally. The output power spectrum was unsymmetrical ω.r.t centre frequency. For $\Delta\omega \neq 0$ one of the reasons for this may be that the spreading in the region of frequencies near the free running frequency of ILO is less as compared to that for frequencies far removed from the free running frequency; and thus if there is frequency offset, the spectrum would become unsymmetrical ω.r.t centre frequency.

Experimental results show that for frequencies more than 5 MHz away from the centre frequency, increasing $\Delta\omega$ from 2 to 4 MHz causes little further spreading of the spectrum. From the experimental results it would appear that such an ILO may be used to obtain a gain $\simeq$ 20 dB for a 5 M bits/sec, 6 GHz MSK signal, however this can be only confirmed after careful testing of the bit error rate.

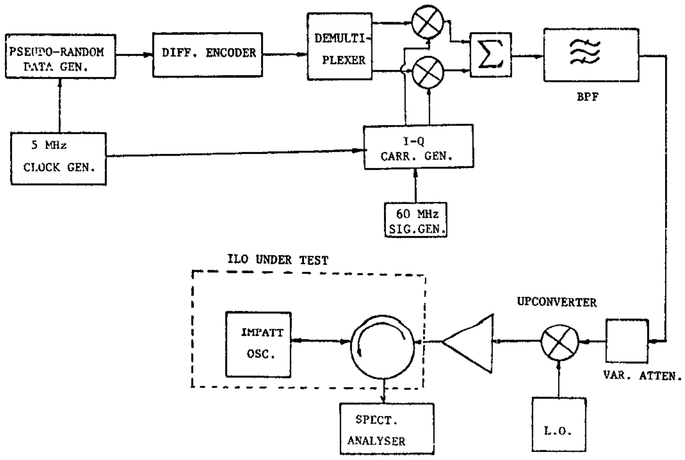

Fig.1 The Experimental Test Set-Up.

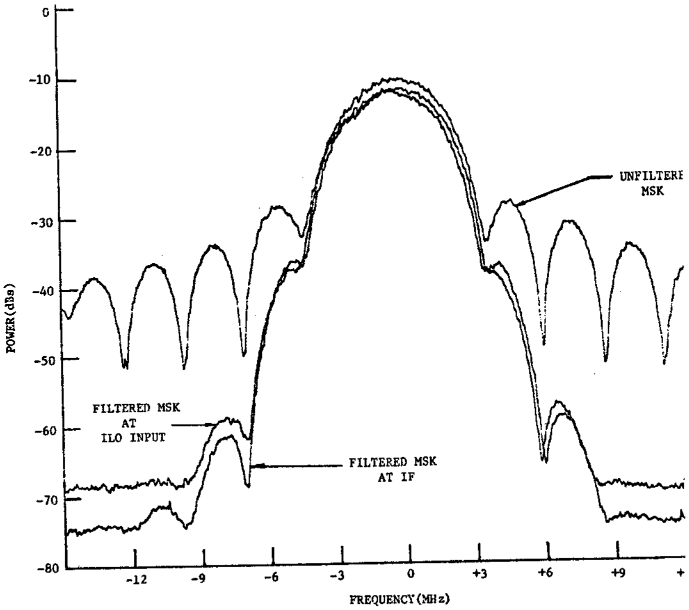

Fig.2 The MSK Filtered and Unfiltered Power Spectra at IF and at the Input to ILO.

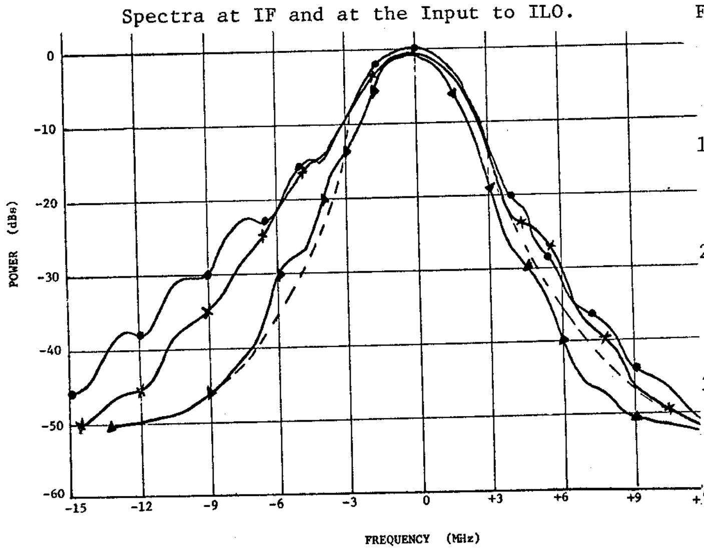

Fig.3(a) Frequency Offset $\omega_o-\omega_i$ = 0 MHz
Experimental: Gains 30dB, 20dB, 12dB
Theoretical : Gain 30dB - - - -

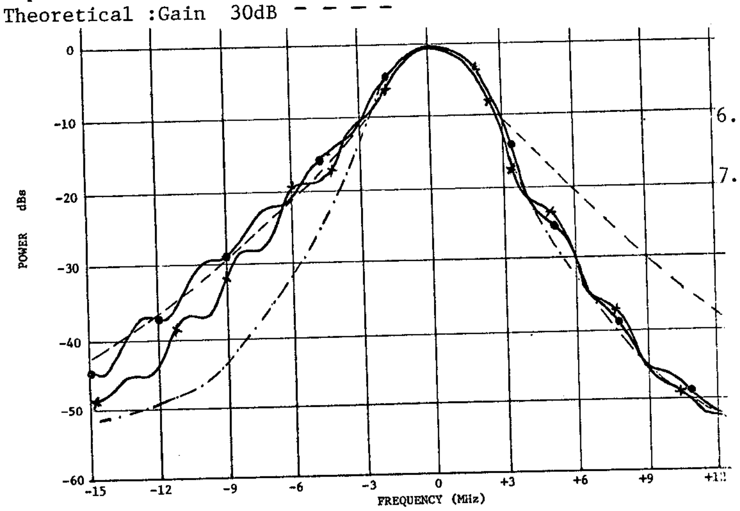

Fig.3(b) Frequency Offset $\omega_o-\omega_i$ = 2MHz
Experimental : Gains 20 dB, 12 dB
Theoretical : Gains 20 dB - - -, 12 dB —·—·—

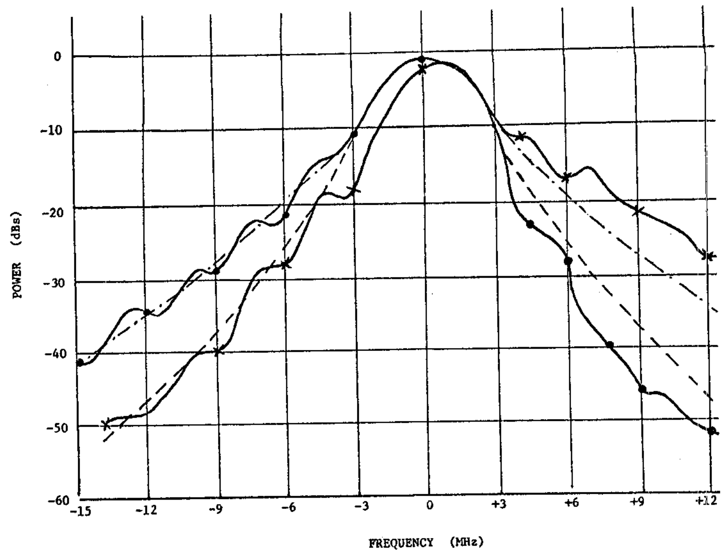

Fig.3(c) Frequency Offset $\omega_o-\omega_i$ = 4MHz
Experimental : Gains 20 dB, 12 dB
Theoretical : Gains 20 dB - - -, 12 dB —·—·—

Figure 3. ILO Output Power Spectra For Various Values Of Gains And Frequency Offset.

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