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SYNCHRONIZATION OF SEMICONDUCTOR DEVICES OSCILLATORS

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Abstract:

The different methods of synchronizing/locking a microwave nonlinear semiconductor oscilator have been presented.

The oscillator model used led to a more general locking equation as the effect of the device nonlinear susceptance is included.

The two experimental techniaues used in the investigation, that is, the sweep-frequency and the spectral analysis techniques give resonable results in agreement with theory.

Introduction

The spectrum purities of solid state oscillators, such as avalanche and Gunn diode oscillators, are found to be much more improved by using synchronization techniques which on the other hand results in a reduction of the existing noise [1].

Four types of synchronization/injection-locking methods have been developed by now, these are:

i. Fundamental-wave injection locking [2]. Here the frequency of the injection signal f_i is nearly equal to the free-running oscillation frequency f_o to be locked.

ii. Subharmonic/Harmonic injection locking [3]. In subharmonic locking, f_i is nearly equal to $1/nf_o$ where as in harmonic locking f_i is nearly to nf_o, where n is an integer larger than unity.

iii. Sideband-wave injection-locking [4]. Here two injection signals are used, one of which is a low frequency signal f_{i1}, and the other a signal with frequency $f_{i2} = f_o + f_{i1}$.

The first and the third techniques have wider locking bandwidth (i.e. tuning bandwidth) than the second, when compared for a particular, gain, with increasing frequency, however, it becomes more difficult to realize a low-noise injection signal source with frequency nearly equal to be stabilized.

The advantage of the second technique is that a low frequency signal can be used for injection. But unfortunately, the tuning bandwidth becomes narrower when the order of multiplication n is increased.

iv. Another technique to overcome the above mentioned difficulties was proposed by Okamoto [5]. It utilizes the parameters interaction which is caused by providing a high-Q idler cavity in the vicinity of an oscillating element and by injecting a signal whose frequency is much lower than the oscillation frequency. This method has much wider tuning bandwidth than of the conventional subharmonic injection locking technique.

To understand the propertiesof injection locking, specially concerning subharmonic and harmonic locking, the general theory developed by Daikoku and Mizushima [6] has been presented. The model used leads to a more general locking equation than Adler's (1964)-[7] as the effect of the device nonlinear susceptance is included. The subharmonic and harmonic locking characteristic do not arise straighforwardly from Kurokawa's (1968) [8].

It is also the purpose of the work to experimentally investigate the process of synchronization in oscillators using both sweep frequency and spectral analysis tecniques.

Theory of Synchronized Oscillators:

In the theoretical study on investigating the synchronized nonlinear diode oscillators, the oscillators nature will be expressed by the nonlinear relation between the instantaneous r.f. current and voltage v. It is assumed that the nonlinear coefficients can be expressed as expanded series of polynomials. Taking v as independent variables, the total current is divided into two parts:

$$\begin{aligned} i_G &= -(G_1 + G_2 v - G_3 v^2)\, v \qquad (1) \\ &= G\,(v)\, v \end{aligned}$$

$$\begin{aligned} i_B &= \frac{d}{dt}\,(C_o + C_1 v + C_2 v^2) \\ &= \frac{d}{dt}\,[B\,(v)\;v]. \qquad (2) \end{aligned}$$

G(v) and B(v) are the "apparent coefficient of nonlinear conductance" and the "apparent coefficient of nonlinear susceptance of the oscillator", respectively. Such representation is possible when steady-state oscillation is considered.

Solving the circuit equation, Fig. 1, and introducting a new variable h representing the degree of detuning, $h = 2\Delta w_o/w_o$ where $h \ll 1$ and $\Delta w = w_i - w_o$; we get a first-order solution for the amplitude and phase at fundamental frequency [6].

$$\frac{dA}{d\tau} = \frac{1}{2}\, gA - \frac{1}{8}\, mA^3 - \frac{1}{2Q'_e}\, U_o \cos Ø\,, \tag{3}$$

$$\frac{dØ}{d\tau} = \frac{1}{2}\, h + \frac{1}{16}\, bA^2 + \frac{1}{2Q'_e\, A}\, U_o \sin Ø \tag{4}$$

The amplitude and frequency of the self-excited oscillation is obtained by putting $U_o = 0$,

$$A^2 = \frac{4g}{m'} \tag{5}$$

$$w'_o = w_o\left(1 - \frac{1}{8}\, bA_o^2\right) = 2\pi f_o \tag{6}$$

where f_o is the free-running oscillation frequency. It is seen that the frequency is shifted from w_o to w'_o by the nonlinear susceptance part, b.

Synchronization of the oscillator to the injection signal is indicated by $dØ/d\tau = 0$ (no beat frequency) and eqn. (4) becomes:

$$\sin Ø = -\frac{Q_e}{2}\sqrt{\frac{P_o}{P_i}}\left(h + \frac{b}{4G}\, P_o\right), \tag{7}$$

Recognizing that the magnitude of sin Ø is less than unity, the boundary between the locked and unlocked modes of operation is characterized by the occurrence of a 90° phase shift between the oscillation signal and the injection signal. The locking relationship may be written in terms of cycle frequency and power as:

$$\left| Q_e\, \frac{P_o}{P_i} \cdot \frac{\Delta w_o}{w_o} + \frac{b}{8G}\, P_o \right| < 1. \tag{8}$$

The above equation becomes and Adler (1964)-[7] and Kurokawa (1968)-[8] equations by putting $b = 0$.

Considering now the behaviour of the locking subharmonic and harmonic injection. The driving frequency w_i is

$$w_i = nw_o\,, \tag{9}$$

where n is the index of the harmonics and $n = 1/2, 1/3, \ldots$ for subharmonic and $n = 2, 3, \ldots$ for higher harmonics. In this case the injection-locked oscillation has a frequency of integral multiple or submultiple of the driving frequency. The same oscillator model can be utilized to study the response to such $\frac{1}{3}f_0$, $\frac{1}{2}f_0$; and $3f_0$ injection signals.

If an equivalent injection signal power is much smaller then the self-excited excited oscillator power, we may consider only the phase equation. A more general locking equation for n = 1/2, 1/3, 2 and 3 is deduced in the form

$$\Delta f/f_o + \gamma p_i = 0 \tag{10}$$

where γ is a parameter depending on n, b and Q.

Experimental Investigation

Two techniques were used in the investigation of the synchronization of the Gunn-diode oscillator used. The first is the sweep frequency technique [9] where investigation is done by sweeping a master source frequency across the frequency f_0 of the unlocked oscillator and observe how the oscillator frequency and output power are influenced. The master source has a linear sweep output, so the horizontal axis of the oscilloscope is directly proportional to the frequency. The second technique is the spectrum analysis one, where the complete spectrum of the drived oscillator is monitored on a spectrum analyzer, which displays it in the frequency domain rather than the time domain.

Measured characteristics of the Gunn-diode oscillator used are shown in Fig. 2 (oscillator type PM 7015 X, Gunn-diode type: PM 7740-CXY11C).

Sweep Frequency Technique

In this experiment we start by sweeping the master source frequency across the frequency f_0 of the unlocked oscillator and investigate how the oscillator frequency and output power are influenced. The measurement set-up is shown in Fig. 3. The master source has a linear sweep output, so the horizontal axis of the oscilloscope is directly propoetional to the frequency. The output power (displaye on channel B) resulted in the power curve drawn in Fig. 4. The locking bandwidth was measured by using the calibrated graticule shown in the same figure.

The previous measurements were repeated for different attenuation values A_2 and the corresponding obtained locking ranges are verified in Fig. 5. It is clear that the locking range decreases with p_o/p_i in agreement with theory. The observed display during measuring procedure is photographed and shown in Fig. 6.

Spectrum Analysis Technique:

For more investigation of the locking phenomena in oscillators, an experiment is constructed based on the use of spectrum analyzer to monitor the output spectrum

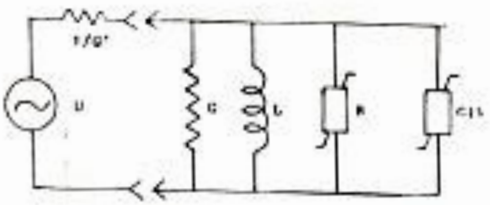

Fig. 1. Semiconductor Device Oscillator Model

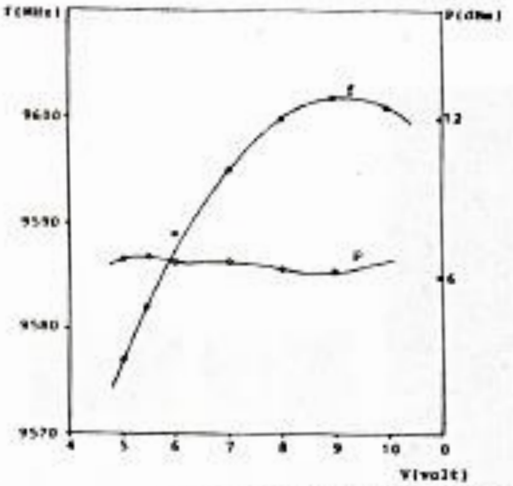

Fig. 2. Power and frequency characteristics of Gunn diode oscillator bias voltage.

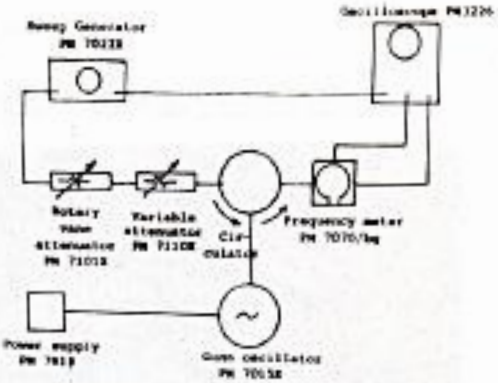

Fig. 3. Measurement set-up to investigate the locking phenomenon by sweep frequency technique.

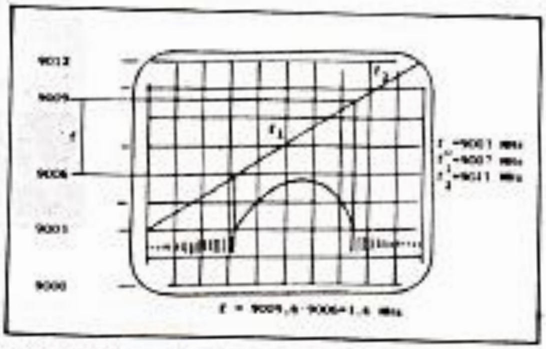

Fig. 4. Calibration graticule (8 x 10 div.) used in determining the locking bandwidth.

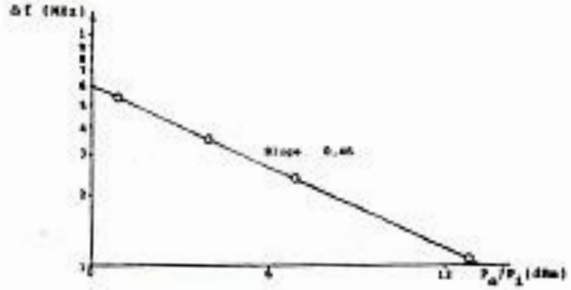

Fig. 5. Locking bandwidth as a function of oscillator to injected signal power using sweep frequency technique.

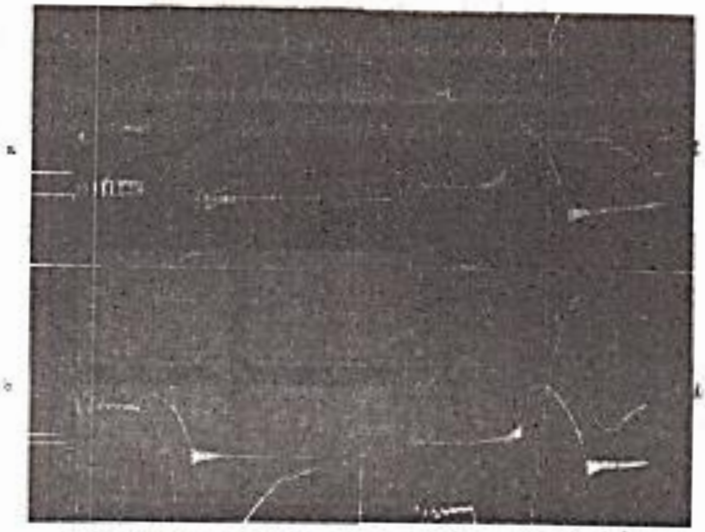

Fig. 6. Observed behaviour of locked oscillatoras the injected power changes to measure variation in locking bandwidth.

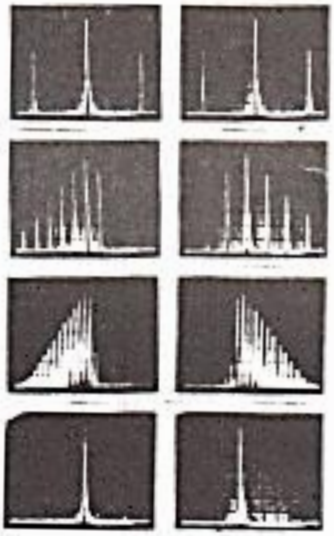

Fig. 7. The generated spectrum before and after locking. A is the injected signal frequency. As A approached B more spectral lines are generated (b&c). The locked frequency is shown in (d). The photos are taken with spectrum analyzer HP-8555A at f_o = 9003MHz, Bandwidth 10 KHz, Scan width 0.5 MHz, and Log. ref. level 10 dB.

of the previously used Gunn-oscillator. The spectrum before and after synchronization is completely interpreted on the analyzer display. The basic idea of spectral analysis is given in [10] and [11].

The spectrum of the disturbed oscillator (before and after locking) is determined by varying the frequency of the injection-signal generator and detecting the appearance of interference sidebands at the end of the locking range on the spectrum analyzer. The detected spectrum is photographed, Fig. 7, at different values of the injected signal frequency A. The oscillator frequency B (f_o = 9003 MHz) is pulled toward the driver frequency w_i through a series of unlocked states say (a-c) or (e-g) till the final locked state is achieved (d) or (h). The spectrum before locking shows unsymmetrical distribution about the driven signal w_o. The same result was achieved by increasing the locking signal level for a given frequency separation between the free running and locking signal. The measured locking range as a function of locking gain was about the same determined by the first method using sweep frequency technique.

It can be seen from the observed spectrum that as w_o-w_i decreases more spectral lines are generated and their spacing is reduced. Moreover, the amplitudes decrease linearly on the logarithmic scale of the spectrum analyzer.

The above spectrum analysis also show that the driven oscillator is unstable unless it is locked. This is in agreement with stability analysis given for performance optimization of injection-synchronized oscillators [2]-and [12].

Conclusions

It has been shown that synchronization of a nonlinear oscillator can be performed by injecting a weak signal of fundamental frequency, subharmonic/harmonic frequency, or sideband frequency. The use of a nonlinear admittance model for the synchronized oscillator was found necessary to explain the unsymmetrical properties of the injection locking.

Typical results were obtained for the Gunn-diode oscillator power/frequency-voltage characterisation. The experimental investigation for the synchronization/locking phenomenon using sweep frequency and spectrum analysis techniques are found to agree with the theory for fundamental injection-locking.

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