MM-Wave Super Harmonic Injection Locked Frequency Dividers

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Abstract

This paper describes the design of a mm-wave super-harmonic injection locked (SHIL) analogue frequency divide-by-2 circuit. The technique exploits the case whereby a saturated amplifier can become unstable and oscillate at exactly half the input frequency. This particular design example operates at an input frequency of 35GHz, but the technique is viable to frequencies approaching the Fmax of the amplifier transistor.

1 Introduction

The concept of injection locking (particularly of one oscillator to another) is a well-known concept in electronic engineering [1]. Also understood, but much less documented, is the phenomenon whereby an overdriven amplifier can be observed to break into oscillation at exactly half the input frequency [2]. This paper will explain how this half-frequency oscillation "problem" can be controlled and exploited. The result is an output oscillation frequency that is effectively injection locked to its super-harmonic frequency (i.e. the fundamental input signal to the amplifier) [3]. The beauty of this technique is that it can be used to easily generate analogue frequency division at any frequency at which an amplifier can be designed. The technique has particularly advantages at mm-wave frequencies where commercially available parts are few and far between.

2 The Concept of Half-frequency Oscillation

As an example, consider a small-signal amplifier designed to amplify an input signal at 35GHz. A typical non-linear (harmonic balance) simulation of such a single-stage 0.25µm gate length pHEMT-based amplifier with a small-signal input (-20dBm) is shown in Figure 1. The transducer gain at 35GHz is approximately 9dB. Note that there is second harmonic content (at 70GHz), but no sub-harmonic content at 17.5GHz.

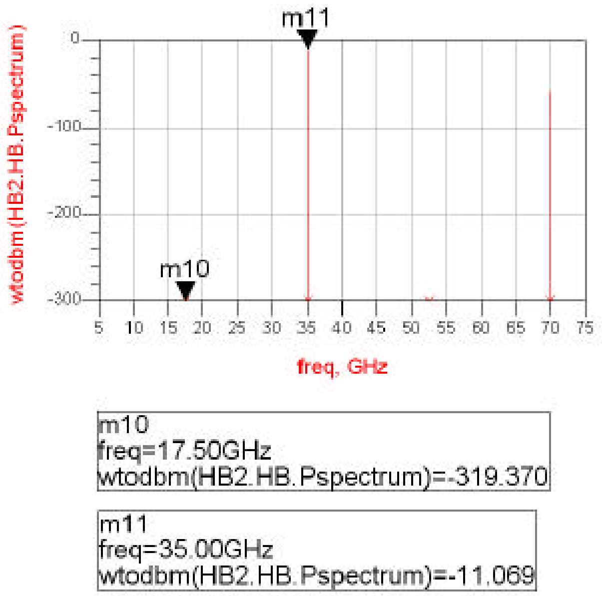

Figure 1: Output Spectrum (Simulated) of a Simple 35GHz Amplifier with –20dBm Input Power

If this amplifier is overdriven, it can be shown [2] that half-frequency oscillation will occur if the amplifier sees a load resistance given by Equation (1).

$$R_L \le \frac{1}{w.C_{gd}} \qquad (1)$$

where: $w = 2p.\left(\frac{F}{2}\right)$ (2)

i.e. ω is the angular frequency at the sub-harmonic of the fundamental frequency, F.

& Cgd is the gate-drain capacitance of the field-effect device.

The non-linear simulation of the aforementioned 35GHz amplifier, for which the condition described in Equation (1) is met is shown in Figure 2. The amplifier is now driven by +20dBm input power. Note that this particular amplifier example has an input-referred 1dB power compression point of +11 dBm, and is therefore shown operating well into compression.

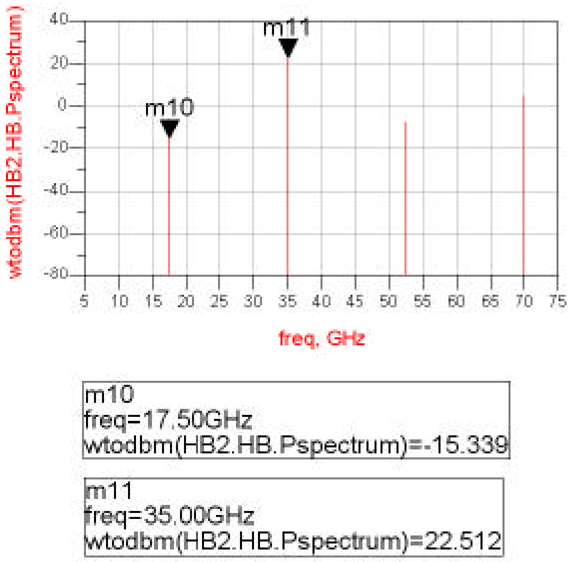

Figure 2: Output Spectrum (Simulated) of the 35GHz Amplifier with +20dBm Input Power

With +20dBm input power the amplifier output is operating approximately 6.5dB into compression. There now exists a half-frequency signal some 38dB below the fundamental.

If this half-frequency oscillation is un-desired, then to suppress this oscillation we have to ensure that the load resistance, RL , is greater than $\frac{1}{w.C_{gd}}$ (3).

This can be easily achieved by incorporating an open-circuit quarter-wave stub (at F/2) one quarter-wavelength away from the pHEMT's Drain (again at F/2), as shown in Figure 3.

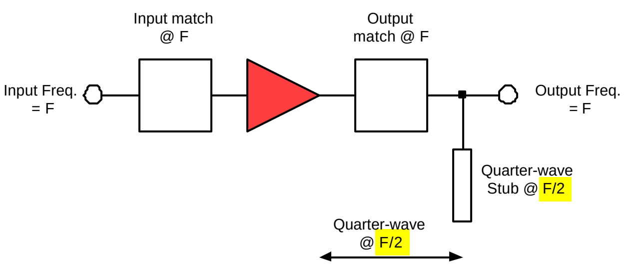

Figure 3: How to Suppress the Half-frequency Oscillation

The load impedance at the output of the pHEMT is now transformed to be open-circuit at F/2, thus easily satisfying the condition of equation (3).

3 The Super harmonic Injection Locked Divider Technique

In order to utilise the phenomenon in an analogue frequency divider, we first design an amplifier in which the load impedance is designed to satisfy the condition of equation (1). The simplest way to achieve this is by re-designing the output match at F/2, and also utilising an open-circuit stub, one-quarter wavelength long, at frequency F, directly on the output of the amplifying pHEMT. The stub ensures that the load looks like a short circuit at F. The output match further suppresses any fundamental breakthrough, and ensures near maximum power transfer at the sub-harmonic, whilst simultaneously satisfying the criterion of equation (1). The circuit concept is illustrated in Figure 4.

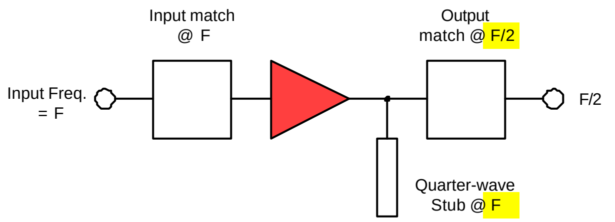

Figure 4: Super Harmonic Injection Locked Divider Circuit

The simulation of the previous amplifier, but with the output circuitry re-designed as per Figure 4 can be seen in Figure 5.

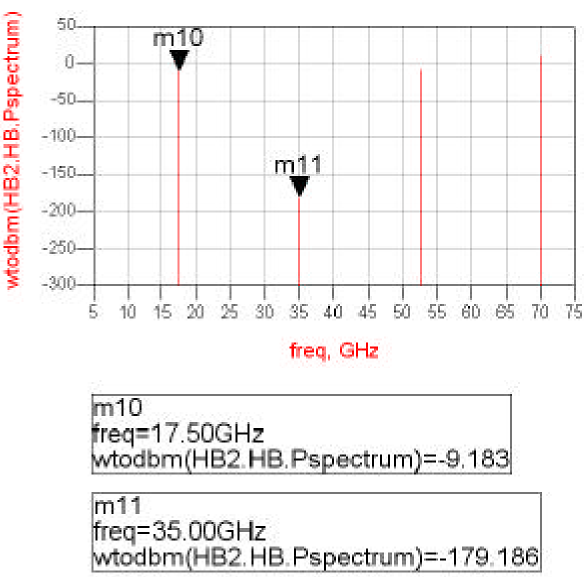

Figure 5: Output Spectrum (Simulated) of SHIL Divider with +20dBm Input Power

Note that the fundamental (35GHz) is well suppressed, and that the equivalent insertion loss of the analogue frequency divider is around 29dB.

Conclusions

An analogue frequency divider circuit can be realised by implementing an amplifier with the output matching circuit designed to satisfy equation (1). This results in half-frequency oscillation that is injection locked to the fundamental input signal. A quarter-wave open-circuit stub at the fundamental frequency, F, can be used directly on the output of the device to terminate the fundamental. By designing the output matching circuit at F/2 rather than F, any fundamental breakthrough can be further suppressed. The resulting circuit is a divide-by-2 circuit with a conversion loss of the order of 30dB. A design example illustrating this technique has been presented using a 0.25μm MMIC pHEMT process. The major advantage of this technique is that it can be used at any frequency at which an amplifier can be designed. This includes well into the mm-wave region for many commercially available MMIC processes. One disadvantage of the technique is the in-efficiency of the circuit (high input powers are required to produce 30dB conversion loss). Similar techniques are also applicable to bipolar transistor based amplifiers. It is also believed that equivalent conditions can be derived for other harmonic division ratios.

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