# Design of Oscillators for Optically Fed MMW Phased Array

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## ABSTRACT

A new approach for design of the optically synchronized millimeter wave local oscillators is introduced based on subharmonically injection locked phase--lock loop technique. The experimental results support the desired goal of frequency and phase coherency of the millimeter wave oscillators, while maintaining the low FM noise degradation and large subharmonic locking range.

## INTRODUCTION

Large aperture phased arrays, composed of many active T/R modules, are envisioned for satellite communication, radar, imaging and surveillance systems. The phase and frequency coherency of these modules can be efficiently obtained by subharmonic injection locking of the local oscillators (LO) via fiber optic (FO) links. The local oscillator can be parametrically stabilized to a reference signal using the nonlinearity of both optical (lasers, electro-optic modulators) and electronic devices (such as HEMT/FET, HBT) in a FO fed phased array architecture. More specifically, laser and FET nonlinearity would create harmonics of the reference signal close to the oscillation frequency of the LO, which results in the fundamental injection locking of the LO, but subharmonic with respect to the synchronizing frequency reference. The synchronization occurs when [1]:

$$\omega_{LO} = \omega_{ref} \times n_{laser} \times n_{osc} + \delta\omega \qquad (1)$$

when $\delta\omega$ is small. Integer number $n_{laser}$ is laser's nonlinearity factor, producing the $n_{laser}{}^{th}$ harmonic of the reference frequency ($\omega_{ref}$) [2]; $n_{osc}$ is the LO's nonlinearity factor, producing the $n_{osc}{}^{th}$ harmonic of injected signal ($\omega_{ref} x n_{laser}$), which is $n_{osc}{}^{th}$ subharmonic frequency with respect to LO's fundamental frequency [3]. $\delta\omega$ is the frequency detuning between the free-running oscillator and the synchronizing signal and for the locked oscillator case is limited to the maximum locking range.

Clearly, the locking range and the noise behavior of subharmonic injection locked LO are highly dependent on the oscillator device nonlinear behavior and the parameters of the feedback network. Even though the injection locked oscillator will provide frequency synchronization, however the initial frequency detuning of $\delta\omega$ would cause an unwanted phase shift of $\pm\pi/2$ over the locking range [4]. To overcome this phase error and obtain phase synchronization an ILPLL circuit was suggested [1]. Two important design tools in achieving optimum subharmonically injection locked oscillators are device nonlinearity and circuit topology. This paper addresses important design requirements of an injection locked oscillator possessing high frequency and phase stability, large locking range, and low phase noise degradation.

## APPROACH

Two figures of merit in the subharmonically locked oscillator, locking range and phase noise degradation, are controlled by the device nonlinearity, device noise power, and the circuit topology of the oscillator. To demonstrate efficient subharmonically locked millimeter wave oscillators, devices capable of having gain above 18 GHz were selected. Commercially available HEMTs from Mitsubishi (MGF4310), were incorporated into the circuit topology shown in Fig. 1.

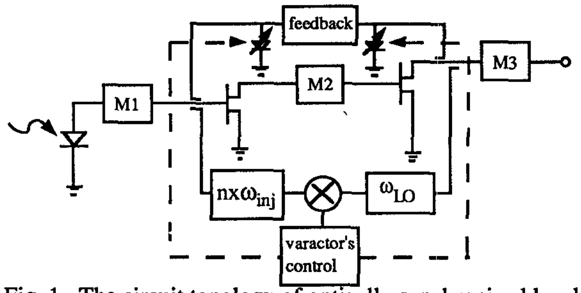

Fig. 1. The circuit topology of optically synchronized local oscillator.

The principle of the circuit topology is as follows:

- The oscillator is constructed by integrating two single stage HEMT amplifiers with parallel feedback from drain of the second transistor to the gate of the first transistor. The feedback resonant network controls the oscillation frequency at about 18GHz.
- The synchronizing signal is injected to the oscillator by building an impedance matching network between the photodetector and the first transistor at $n_{osc}{}^{th}$ subharmonic of the LO frequency.
- The phase synchronization is obtained by the phase comparison of $\omega_{inj} x\ n_{osc}$, sampled at the output of the photodetector with $\omega_{LO}$, which is the sampled output of the

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LO. The phase error information is used to adjust the resonant frequency of the feedback network by adjusting capacitance of the varactor diodes.

## DESIGN AND REALIZATION OF OSCILLATOR

Two MIC based 18GHz oscillators were designed and fabricated on RT/Duroid, similar to the one shown in Fig.1. The oscillator circuit consists of an input branch line coupler, a dual stage amplifier, an output branch line coupler, and a varactor tuned gap resonator in the feedback loop. The resonator is a $\lambda/2$ open transmission line with a Q factor of around 100.

A single stage amplifier was built first with 10 dB of gain from 17 to 19 GHz. Coupled line filters were used for DC isolation, ease of fabrication, and for reducing gain at lower frequencies. A quarter-wave impedance transformer was used to impedance match $S_{11}$ and $S_{22}$ of the HEMTs. The dual stage amplifier was then built by cascading two single stage amplifiers, which resulted in a 20 dB gain over 17 - 19 GHz. The 18GHz oscillator was realized by providing feedback from the output to the input of the cascaded amplifiers through a network consisting of input and output couplers, and the gap resonator. The resonant circuit acts as a tunable bandpass filter from 17.8 to 18.4 GHz. The input branch line coupler was designed for -3 dB coupling at 9 and 18 GHz, in order to perform efficient injection locking at fundamental and 2nd subharmonic frequencies.

Each oscillator operated around 18.3 GHz. Oscillator 1 had a free running frequency of 18.268 GHz, with a tuning range of 88 MHz. Oscillator 2 had a free running frequency of 18.166 GHz, with a tuning range of 161 MHz. The output power for both oscillators was approximately 10 dBm. These oscillators operate in either the free running mode, or injection locked with either a 9GHz or 18 GHz frequency reference signal.

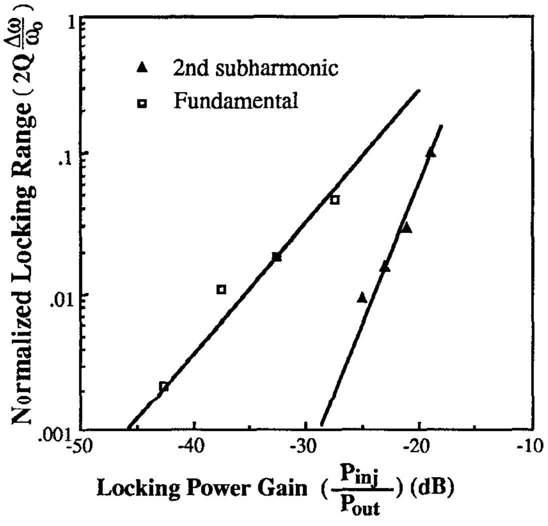

Fig.2 Normalized locking range of oscillator 1 at 18GHz as a function of the locking power gain for fundamental and 2nd subharmonic frequency.

## EXPERIMENTAL RESULTS

First the subharmonic injection locking property of the oscillator was investigated. Since the overlap tuning frequency of the two oscillators was only 58.8 MHz (cf. previous section), the oscillators were tuned to the approximate frequency of 18.28 GHz. Fig. 2 shows the normalized injection locking range of oscillator 1, varying with injection locking gain, as a representative of both oscillators behavior.

Phase noise of the subharmonically locked oscillator varying with injection power is shown in Fig. 3. When the injection power is small, FM noise is dominated by LO intrinsic noise, and the FM noise decreases with input power at a rate of 2:1 in logarithmic scale. When injection power is large enough, the FM noise reaches to a level which is 6dB (20Log[n], n=2) above the injection signal's FM noise. We may also observe that for injection power gain levels of about -20dBm (corresponding to -10dBm injected power, which is what we optimally could achieve at the output of a synchronizing fiber-optic link), the FM noise degradation reaches its minimum level, while the normalized locking range is at a desirable $10^{-1}$ range [3].

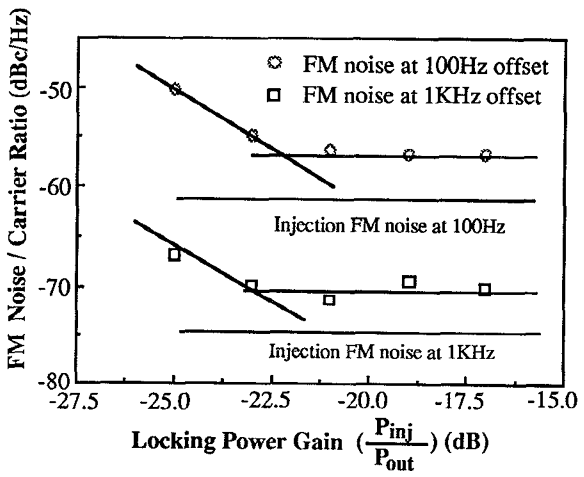

Fig. 3 FM noise degradation of the subharmonically locked oscillator 1 as a function of the locking power gain.

Both oscillator were then injection locked with the same subharmonic reference signal of 9.144 GHz at power level of -10dBm. An HP8510B with a HP8511A harmonic frequency converter was used to compare the sampled input and outputs of each oscillator simultaneously. A 10 dB coupler was used to sample the frequency reference, and 20 dB coupler was used to sample the output of two oscillators. The sampled output of the input reference signal was doubled to the frequency of 18.288 GHz. The sampled outputs from each oscillator were then compared to the doubled input sample at the harmonic converter.

Fig. 4 shows the phase response of the two oscillators while being subharmonically injection locked.

From this plot, a 2nd subharmonic locking range of 14 MHz and 4 MHz was achieved for oscillator 1 and oscillator 2 respectively. Once both oscillators were subharmonically injection locked to the reference frequency of 9.144 GHz, the free running oscillation frequency of oscillator 2 was tuned by changing the bias voltage on the varactor diode. As a result of this tuning, since the frequency of the injection locked oscillator is fixed, the phase would shift over -90° to +90° over the locking range. Fig. 5 depicts a full 180 degrees phase shift control in 11.25 degree increments. This method presents a viable method to change the output phase of the oscillator. However, it should be mentioned that a FM noise degradation of 6dB was measured at an output phase 80° as compared to the phase 0°. This phase noise degradation can limit the total phase shifting range to only ± 45°.

Next phase locking of the injection locked oscillator 1 was established using an ILPLL technique [4]. Phase comparison of the injection locked oscillator with frequency reference is employed to detect for the phase error of the oscillator. This phase comparison is achieved using the circuit shown in Fig. 6, where the phase error correction is established by comparing the phase of the reference signal with that of the subharmonically injection locked oscillator. The phase locking process is established by adjusting the free-running oscillation frequency. An ILPLL circuit, was constructed for oscillator 1 takes advantage of the input reference signal ($\omega_{ref}$=9.144 GHz), which is sampled via a 10 dB coupler and doubled using a multiplier. The frequency doubled signal at 18.288 GHz is then passed through a 18 GHz highpass filter, realized using a K-band metallic waveguide. The output of the oscillator is also sampled using a 20 dB coupler and highpass filtered similar to the reference path. These two signals then are mixed using a balanced mixer. The phase difference of the two signals corresponds to a DC voltage in the frequency locked case, which is then amplified using MMIC operational amplifiers and used to control the bias of the varactor diode. Fig. 7 depicts the phase control of the oscillator achieving stable frequency and phase over locking range of 25MHz. It should be noted that by adjusting the $V_{ref}$ of the operational amplifier, stabilized phase shifts of -90 to +90 was observed.

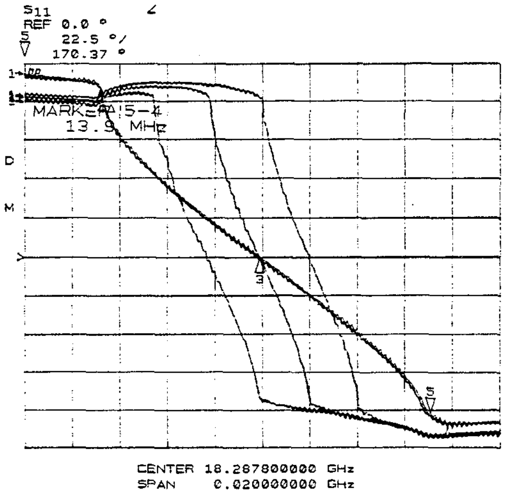

Fig. 4. The phase responses of the subharmonically injection locked Oscillator 1&2. (The vertical scale of 22.5°/div, the horizontal scale of 2MHz/div, and the reference level at 0°)

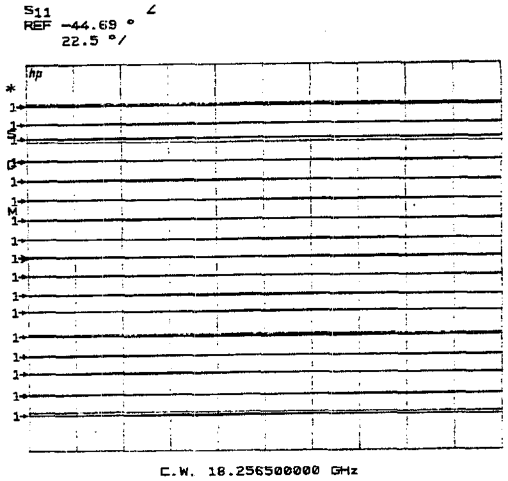

Fig. 5 Phase shift of a subharmonically locked oscillator by changing the varactor voltage (The vertical scale of 22.5°/div, the frequency of 18.256GHz, and the reference level at 44.7°).

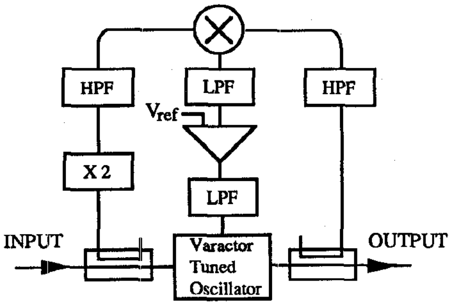

Fig. 6 Block diagram of the subharmonic ILPLL.

## CONCLUSION

A new approach for design of the optically synchronized millimeter wave local oscillators is introduced, satisfying frequency and phase coherency necessary in distributed local oscillators. The design approach is based on the subharmonic injection locking of an ILPLL oscillator. Two oscillators at 18GHz were designed and constructed to demonstrate validity of this approach. Large normalized locking range and low FM noise degradation were demonstrated. In addition, the phase locking method was extended to achieve stabilized phase shift of ±90°. The proposed oscillator design can be easily implemented on MMIC circuits at millimeter wave frequencies, where prohibitive loss of phase shifters and frequency and phase instability of local oscillators are problematic.

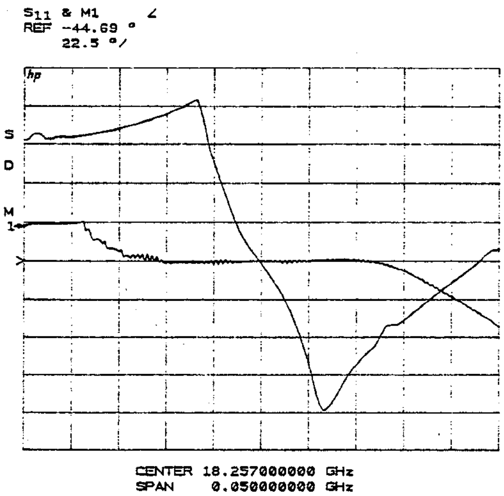

Fig. 7 Phase response of injection locked oscillator 1 with (Curve 1) and without (Curve 2) phase locking. (The vertical scale of 22.5°/div, the horizontal scale of 5MHz/div, and the phase reference level of 44.7°.)

## ACKNOWLEDGEMENTS

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