# A PUSH-PULL SELF-OSCILLATING MIXER FOR OPTICALLY FED PHASED ARRAY

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## ABSTRACT

The optical control of the distributed electronics in phased array antennas requires specialized circuits which are compatible with the T/R level data mixing architecture. This paper presents a novel circuit, a push-pull self-oscillating mixer, that can perform three important functions: 1) oscillation, 2) frequency and phase locking to a reference signal, and 3) mixing with the data signals. This proposed circuit performs these three functions efficiently in a low power consuming circuit. Until now, these functions could be done only through independent circuits. This concept was analyzed and experimentally demonstrated at 12 GHz by use of a MESFET pair with a measured conversion efficiency as high as 13 dB and noise figure of 9 dB. Efficient subharmonic injection locking was also demonstrated. This design can be easily extended to HEMT and HBT at higher frequencies.

## INTRODUCTION

In optically controlled phased array antennas for satellite communication at millimeter wave frequencies, fiberoptic links provide frequency reference signals to synchronize distributed local oscillators and data signals to or from T/R modules [1]. Figure 1a. depicts conceptually the optical distribution network to control the subarray antennas in the transmit mode of operation; Fig. 1b shows the T/R level data mixing architecture [2] in phased array antennas in the receive mode of operation .

In the transmit mode of operation, the output of the mixer is the modulated carrier used for radiation out of the array; in the receive mode of operation, the output of the mixer is the received data signal needed for signal processing at the central processor. One of the challenges of the integrated interface between the MMIC T/R modules of the optical receiver and transmitter is how to achieve the high efficiency and quality performance of the components labeled as *local oscillator/mixer* box, which can perform: 1) subharmonic injection locking of the microwave and millimeter wave oscillator by the frequency reference, while maintaining low FM noise degradation, large locking range, and large subharmonic factors; 2) phase locking of the injection locked oscillator to stabilize phase of the injection locked oscillators to the frequency reference; 3) efficient mixing of the IF/RF data signals with the stabilized local oscillator, providing high conversion efficiency and low noise figure.

The goal of this paper is to present a new circuit, a push-pull self-oscillating mixer which can perform the above three functions efficiently. The design was directed at 12 GHz to demonstrate the merits of this design. However, it can be scaled up to millimeter wave frequencies with appropriate devices, such as HBT and HEMT.

## APPROACH

Two figures of merit in the subharmonically locked oscillator, locking range and phase noise degradation, are controlled by the nonlinearity and noise characteristics of the device and the circuit topology of the oscillator [3]. The most important figure of merit for mixers, conversion gain/loss, also depends on the device nonlinearity and the circuit topology of the mixer [4]. However nonlinearity can be controlled by using the fabrication geometry of the devices and selecting an appropriate operating point. Quite often, the operation point for a FET oscillator is class A, but for a FET mixer, operating points close to class B are preferred. When operating close to class B, the nonlinearity of the FET device can be enhanced. Large nonlinearity increases the subharmonic injection locking range of the oscillator and thus minimizes the phase noise degradation [3] and enhances the conversion gain of the mixer [4].

A new circuit topology, shown in Fig. 2, called a Push-Pull Injection Locked and Phase Locked Self-Oscillating Mixer, is proposed in this paper to achieve optimum mixing and oscillation characteristics. The principles of operation for the circuit topology are as follows:

- The oscillator is constructed by integrating parallel feed back from the drain(s) to the gate(s) of a FET pair of a push-pull amplifier. Transmission lines provide 180° phase shift at $f_{LO}$ between the gates and the drains of the two transistors.
- The synchronizing signal is subharmonically injected to the push-pull oscillator from port 1 to lock the free running oscillator frequency.
- The phase synchronization to the reference signal is obtained by the phase lock loop. A varactor diode incorporated in the feedback circuitry tunes the free running oscillator to reduce phase difference between the synchronization signal, $f_{inj}$, and output signal $f_{LO}$.
- The inputted RF/IF signal from port 2 is mixed with the stabilized LO, and the down/up-converted IF/RF signal is outputted from port 3.

Since the two FETs are biased for quasi-class B operation, the large locking range for the oscillator and the high frequency conversion gain for the mixer can be achieved simultaneously and efficiently.

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## ANALYSIS

The analytical modeling of this circuit is based on the nonlinear I-V relationship of the transistor. More specifically, a power series is used to relate the drain current of FET to gate voltage as

$$I = a_1 V + a_2 V^2 + a_3 V^3 + \cdots \qquad (1)$$

The parameter $a_i$ are unknown coefficients which can be directly derived from nonlinear model of devices.

From this power series nonlinear relationship, the subharmonic injection locking range and mixer frequency conversion efficiency can be derived.

a) Subharmonic Injection Locking Range:

The input voltage of two transistors T1 and T2 for this circuit can be presented as

$$V_1 = E_o \cos\omega_{LO} t + E_{inj}\cos(\omega_{inj} t + \varphi)$$

$$V_2 = -E_o \cos\omega_{LO} t + E_{inj}\cos(\omega_{inj} t + \varphi + \frac{\pi}{n})$$

where n is the subharmonic factor used in the subharmonic injection locking of the push-pull oscillators i.e. $\omega_{inj} \approx \frac{\omega_{LO}}{n}$, and $\varphi = \pm\frac{\pi}{2n}$. The feedback circuit satisfying the transfer function of $H(\omega)$ is employed to predict the subharmonic locking range using Harmonic Balance method [5]. The expected locking range is derived as:

$$\Delta\omega_{\frac{1}{2}} = \frac{\omega_o}{2Q}\frac{E_{inj}}{E_o}\frac{2a_2E_{inj}}{4a_1 + 3a_3(E_o^2+E_{inj}^2)} \qquad n=2 \qquad (2)$$

$$\Delta\omega_{\frac{1}{3}} = \frac{\omega_o}{2Q}\frac{E_{inj}}{E_o}\frac{a_3E_{inj}^2}{4a_1 + 3a_3(E_o^2+E_{inj}^2)} \qquad n=3 \qquad (3)$$

b) Mixer Conversion Gain:

The input voltage to the transistor T1 and T2 are represented by

$$V_1 = E_o\cos\omega_o t + E_{RF}\cos(\omega_{RF} t + \theta + \Delta\theta)$$

$$V_2 = -E_o\cos\omega_o t + E_{RF}\cos(\omega_{RF} t + \theta)$$

where $E_{RF}$ is the amplitude of the received RF signal to be down-converted by the local oscillator and $\Delta\theta$ is the phase shift introduced by the transmission line, i.e., $\Delta\theta = \frac{\omega_{RF}}{\omega_{LO}}\pi$. From Eq. (1) and by use of Harmonic Balance, the downconverted signal is calculated and the conversion efficiency is expressed as

$$G_c = 4\, g_1^2\, \mathrm{Re}\{Z_{RFin}\}\mathrm{Re}\{Z_{IFLoad}\} \qquad (4)$$

where $g_1 = a_2 E_0$.

We have derived $a_i$ parameters for a MESFET transistor from NEC (NE720) to compare the predicted performance of the self-oscillating mixer to the measured results.

## EXPERIMENTAL RESULTS

To demonstrate the merits of the proposed push-pull self oscillating mixer, a circuit was designed and fabricated according to the concept shown in Fig. 2. The NEC (NE720) MESFET transistors were characterized to extract the nonlinear I-V coefficients. The nonlinear equivalent circuit model of the FET was also separately derived by fitting the predicted S parameters to the measured S parameters over a wide range of bias points. The key nonlinear parameters, $a_1$, $a_2$ and $a_3$ were then derived, as shown in Fig. 3, to verify our theoretical analysis. Finally, the push-pull self oscillating mixer circuit topology was designed and simulated using the nonlinear model of the NEC transistor via a nonlinear CAD simulator.

The initial test results of this circuit were extremely positive. We were able to demonstrate oscillation at frequency of 11.8 GHz with an output power being up to +13dBm for $V_d$=3V and $V_{gs}$=-0.5V. We had the oscillator injection locked fundamentally and subharmonically to an HP 8340B synthesizer. A major reduction in the close-in to carrier FM noise level was observed[6]. The second subharmonic injection locking range performance, depicted in Fig. 4, shows a good match for the predicted and the measured second subharmonic injection locking range. To the best of our knowledge this work is the only work demonstrating the injection locked push-pull oscillator design.

In the second set of measurements, we investigated the mixing performance of this self-oscillating mixer. A conversion gain as high as 13dB is measured for the $V_{gs}$=-1.82 V, which corresponds to the LO output power of +2 dBm. The total power consumption of this self-oscillating mixer is about 60 mW. The predicted and the measured conversion gain as a function of the gate bias matched very well, as depicted in Fig. 5. Conversion gain as a function of the RF power level for different operating points was also measured, as depicted in Fig. 6. The mixer conversion gain is flat up to $P_{RF} \cong$ -10dBm. Noise characteristics of this mixer was also characterized. A noise figure of 9 dB was measured for down conversion from 16.8 GHz to 5 GHz. Additional measurements are still in progress.

## DISCUSSION

The first injection locked push-pull self-oscillating mixer has been designed and tested. This circuit provides for low power consumption, high subharmonic injection locking range, and high frequency conversion efficiency. The calculated performance matched very well with the measurement results. The details of 'a' parameter extraction technique is not discussed here due to the space limitations.

Now we feel that because of efficient performance of this topology, this small size and low power consuming injection locked push-pull self-oscillating mixer is attractive for T/R level data mixing architecture [1] of the optically fed phased array antennas .

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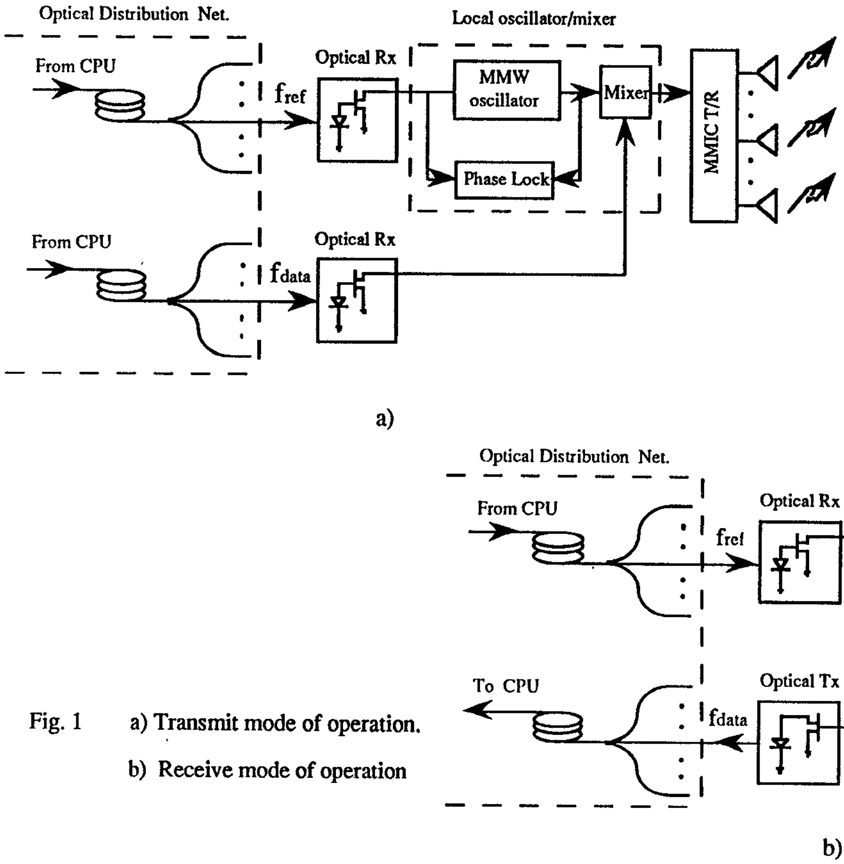


Fig. 1 a) Transmit mode of operation.

b) Receive mode of operation

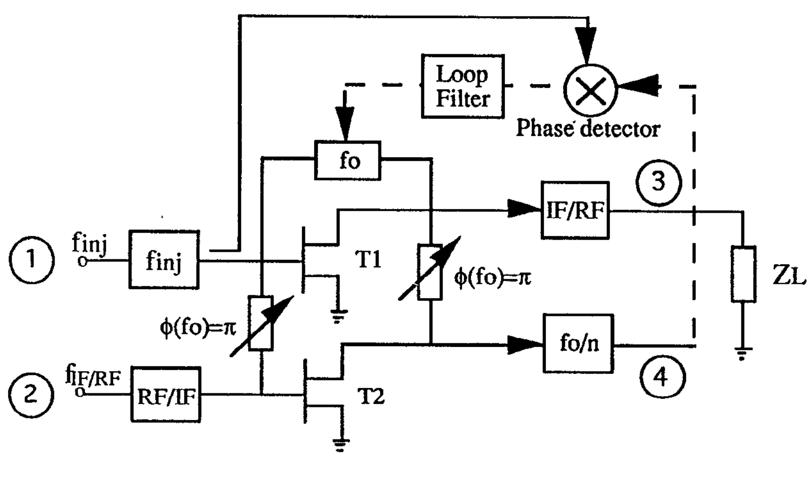


Fig.2 The schematic diagram of the Push-Pull Injection Locked and Phase Locked Self Oscillating Mixer. The finj block is for injection signal input , the RF/IF block is for RF/IF signal input, the IF/RF block is for IF/RF signal output, and the fo/n block is for fo/n signal output, which is provided to phase lock loop for phase comparison.

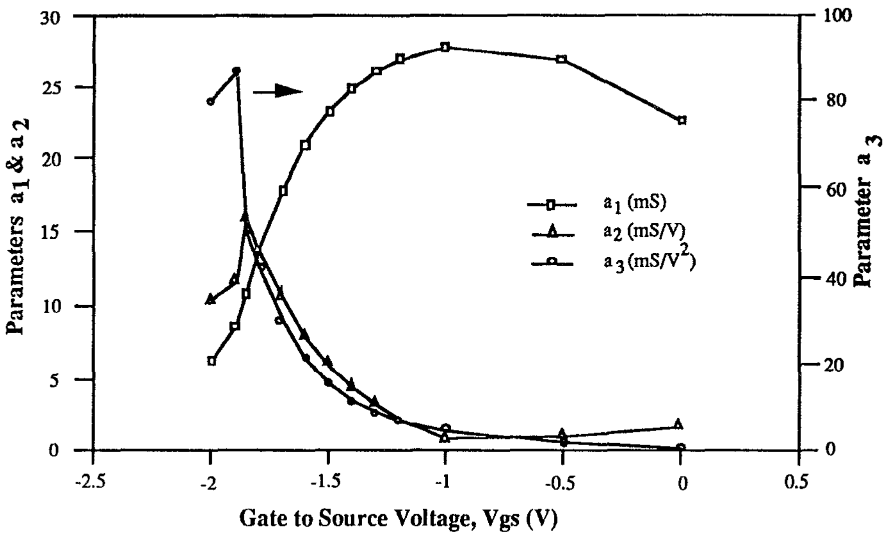


Fig. 3 Nonlinear parameters, $a_1$, $a_2$, $a_3$, derived from NE720 MESFET nonlinear modeling, as functions of device bias voltage.

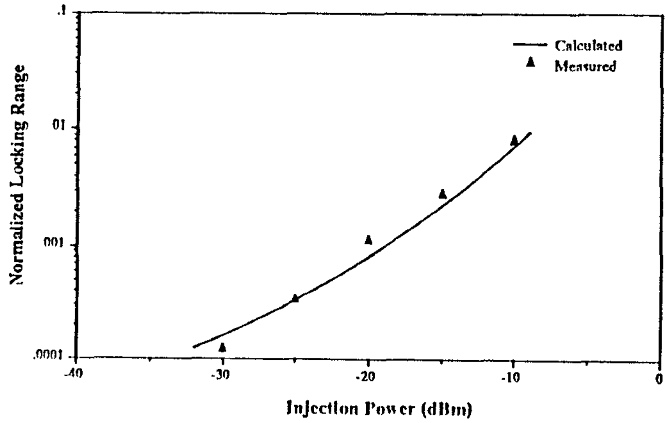


Fig. 4 Measured and predicted second subharmonic injection locking range.

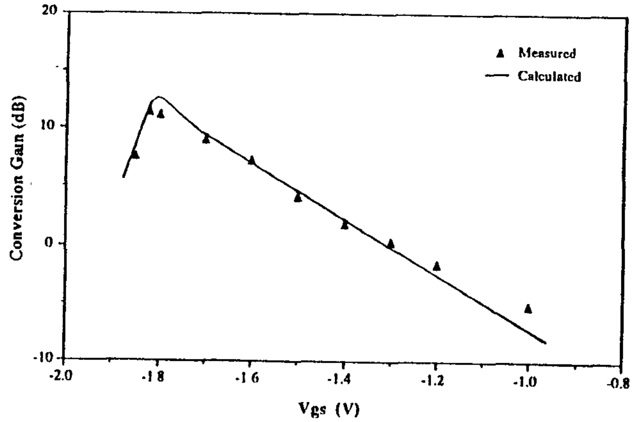


Fig. 5 Measured and predicted frequency conversion gain of the circuit as a function of device bias voltage.

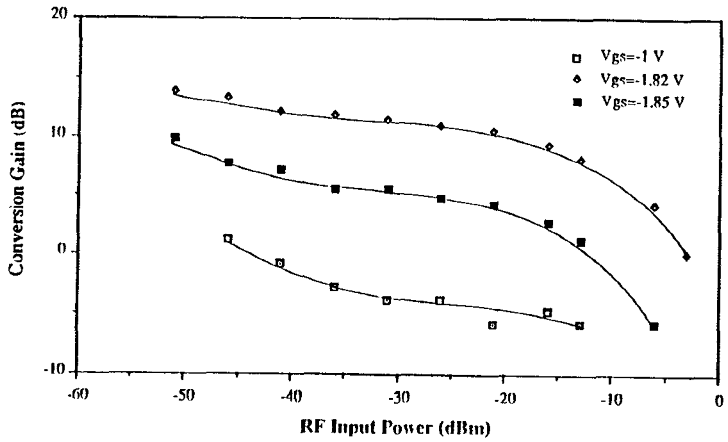


Fig. 6 Frequency conversion Gain vs. RF input power at different gate bias points.