Phase Modulation of a Loop Phase-Locked Grid Oscillator Array

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***Abstract*—In this letter, we describe a method for phase modulation of a loop phase-locked grid oscillator array and report results obtained in a test bed implementation of the method. The key to the scheme lies in introducing the phase-locked loop (PLL) in such a way that the modulating data stream is introduced in parallel with the loop rather than through it, thereby circumventing the bandwidth limitation of the PLL. The experiment was performed at 4.7 GHz with a phase-locked grid oscillator array. The grid oscillator was successfully modulated by a 1 MHz signal, which is ten times higher than the bandwidth of the phase-locked loop.**

***Index Terms*—Grid oscillator, phase-locked loop, phase modulation, spatial power combining.**

I. Introduction

SPATIAL power combining provides an efficient way of achieving high power from solid state devices at microwave and millimeter wave frequencies [1]–[7]. A frequency-stabilized power combining oscillator array, when properly modulated by a base band signal, can be used directly as transmitters for communication or radar applications [8], [9].

Classically, phase modulation can be implemented with a phase modulator [8] or through a phase-locked loop (PLL) [9], [10]. A phase modulator, usually consisting of delay lines controlled by switching devices such as PIN diode switches, introduces significant insertion loss and may cause linearity problem. Phase modulation though a PLL is accomplished by adding the modulating signal to the output of the phase detector. The PLL attempts to maintain the sum voltage at a null by generating a phase error voltage that cancels the modulating signal. This method, however, has limited modulation bandwidth, or data transmission rate for digital communication systems, due to the limitation imposed by the bandwidth of the PLL. When the modulating signal operates at a frequency much higher than the loop bandwidth, it will be filtered out before reaching the voltage-controlled oscillator, and, thus, no modulation can be achieved.

In this letter, we report our work on the phase modulation of a loop phase-locked grid oscillator array, in which we attempted to overcome this bandwidth limitation due to the phase-locked loop.

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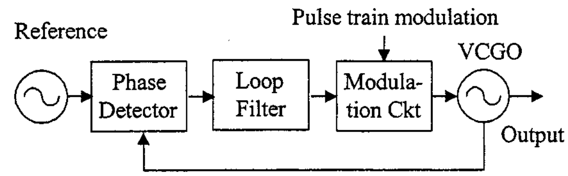


Fig. 1. Phase modulation using a phase-locked loop.

II. Phase Modulation Principle

Fig. 1 illustrates the block diagram of the proposed scheme of phase modulation of a grid oscillator array. The system consists of a voltage controlled grid oscillator array (VCGO), a phase detector, a loop filter, and a phase modulation circuit. The detail of the loop phase-locked grid oscillator is discussed in [11]. The modulation signal is applied to the VCGO through a modulation circuit inserted between the loop filter and the VCGO. In this way, the phase-locked loop is used only for stabilizing the frequency. When the modulation signal, whose frequency is much higher than the loop bandwidth, is introduced to modulate the voltage controlled grid oscillator, the loop does not respond to this modulation signal. Hence, it is possible to overcome the limit imposed by the bandwidth of the phase-locked loop and obtain high data rate transmission.

Fig. 2 shows the schematics of the modulation circuit. The modulation signal is capacitively coupled to the VCGO. This converts the square wave signal into pulse signal. The two resistors R_1 and R_2 reduce the effects of the source resistance of the external generator supplying modulation signal. The modulation signal and the error voltage from the loop filter are added together and applied to the VCGO. The phase change due to the pulse modulation can be obtained from

$$\varphi = \int_0^t \Delta\omega(t)\, dt \quad (1)$$

where $\Delta\omega(t)$ is the frequency change due to the modulation signal. By assuming that the oscillation frequency of the VCGO changes instantly with the tuning voltage, the frequency change can be represented in terms of an exponential function as

$$\Delta\omega(t) = K_{\mathrm{VCO}}\Delta V(t) = \pm K_{\mathrm{VCO}} V_p e^{-t/(RC)} \quad (2)$$

where

$$R = R_1' + R_2' \quad (3)$$

and

$$V_p = \frac{R_2'}{R_1' + R_2'} V_e. \quad (4)$$

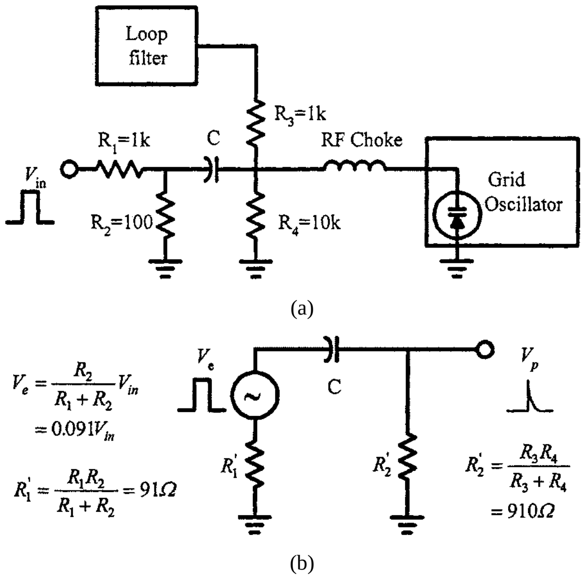


Fig. 2. (a) Schematics of the phase modulation circuit (b) and its equivalent circuit.

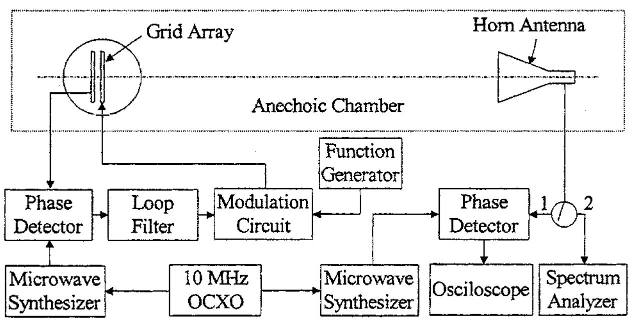


Fig. 3. Phase modulation and demodulation setup.

Substituting (2) into (1) and using the conditions that the time constant RC is much smaller than the period of the modulation signal and that the frequency of the modulation signal is much higher than the loop bandwidth, the phase shift due to the modulation signal can be simplified as

$$\varphi = \pm K_{\text{VCO}} V_p RC. \tag{5}$$

It can be seen that the modulated phase is determined by the frequency tuning sensitivity of the VCGO, the modulation signal magnitude, and the time constant of the modulation circuit. We targeted the modulation frequency to be 1 MHz for the 4.7 GHz loop phase-locked 4×4 grid oscillator array. By setting $\varphi = \pm\pi/2$ and substituting K_{VCO} (=20 MHz/V) into the above equation, one obtains

$$V_p RC = 1.25 \times 10^{-8}\ \text{V} \cdot \text{S}.$$

As mentioned before, a reasonable choice of the time-constant in the modulation circuit is that the value of RC must be much smaller than the period of the modulation signal. Thus we choose $RC = 2.5 \times 10^{-8}$ S and one can see that $C = 25$ pF and $V_p = 0.5$ V. Since this time constant is much smaller than the time constants in the loop filter, its effect on the loop performance is negligible. We should also mention that the input data stream is restricted to have a zero mean value, thereby limiting the modulation schemes that are compatible with our modulation scheme. Any nonzero mean value would cause the loop to pull back the desired phase shift due to the modulation.

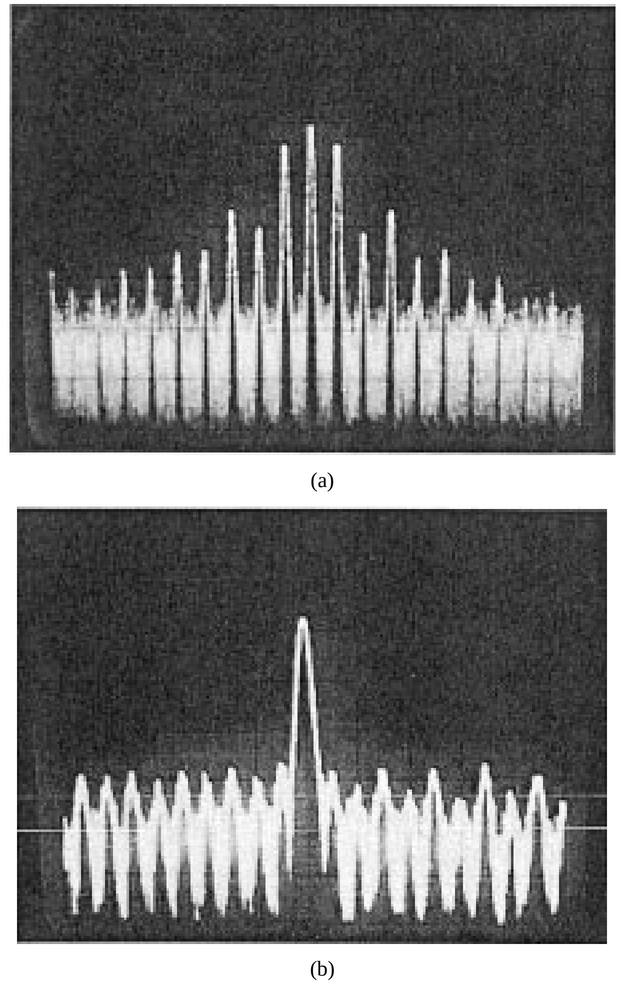
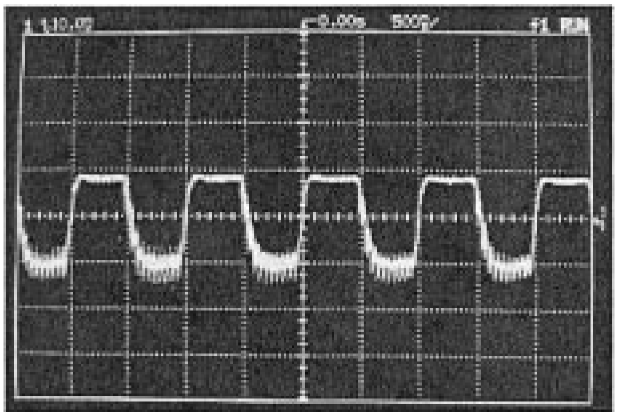


Fig. 4. Spectra of modulated signal: (a) 1 MHz modulation, span 1 MHz/div, spectrum analyzer filter bandwidth 10 kHz; (b)10 kHz modulation, span 10 kHz/div., spectrum analyzer filter bandwidth 1 kHz. Both at center frequency of 4.63 GHz and with vertical scale of 10 dB/div.

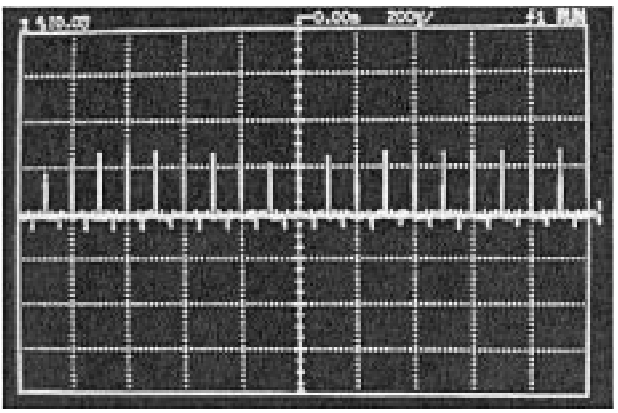
III. Measurement Results

The modulation circuit designed was added between the output of the loop filter circuit and the varactor diode input of the grid oscillator phase-locked loop. The test setup is sketched in Fig. 3. The modulated grid oscillator signal is detected by a receiving horn antenna that is connected to a spectrum analyzer or a phase detector. A function generator was used in the experiment to provide square wave modulation signal. Two modulation signal frequencies were chosen for showing the principle. One was 1 MHz, which is higher than the loop bandwidth (100 kHz), the other was 10 kHz, which is much lower than the loop bandwidth.

The spectrum of the modulated signal was observed with a spectrum analyzer. Fig. 4(a) shows the spectrum of the received signal when the grid oscillator was modulated by a 6.5 V_{p-p}, 1 MHz square wave signal. The side band frequencies indicate



(a)



(b)

Fig. 5. Demodulated signal: (a) 1 MHz modulation, vertical scale 10 mV/div., horizon; scale 0.5 μS/div.; (b) 10 kHz modulation, vertical scale 10 mV/div., horizon; scale 0.2 mS.

that the grid oscillator was modulated by the 1 MHZ signal successfully. For comparison, the grid oscillator was also modulated by a 10 kHz signal and the spectrum was given in Fig. 4(b). Since the modulation signal frequency is much lower than the bandwidth of the phase-locked loop, the phase difference caused by the modulation signal is cancelled by the phase-locked loop and hence no phase modulation is achieved.

In order to recover the modulation signal, an identical phase detector was used with its LO port driven by a frequency synthesizer whose frequency is set to the same as the carrier frequency (PLL reference frequency). Both frequency synthesizers are locked to the same reference crystal oscillator. Fig. 5 gives the photographs of the demodulated signals taken from the screen of the oscilloscope. When the grid oscillator is modulated by a 1 MHz signal, the modulation signal can be recovered very well as in Fig. 5(a). It is not surprising that the 10 kHz modulation signal cannot be recovered due to the phase-locked loop. Actually, only a very narrow pulse signal was detected as is shown in Fig. 5(b).

IV. Conclusion

The idea of using a phase-locked loop to modulate the phase of the grid oscillator has been tried and successful results were obtained by introducing the modulation signal to the output of the loop filter. The frequency of modulation signal reached 1 MHz, which is ten times the bandwidth of the phase-locked loop. The modulated signal was also demodulated and the original modulation signal was recovered at the receiving end. The disadvantage of this method is that it requires that the modulation signal be zero mean. This requirement restricts its application and approaches to overcome this disadvantage are being investigated in Clemson University.

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