Full 360° Phase Shifting of Injection-Locked Oscillators

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***Abstract*— A novel design is presented to produce analog phase shift of 0° to 360° in optically controlled oscillators which are subharmonically injection-locked. The proposed concept was analytically described and experimentally demonstrated by producing 360° of phase shift in an 8 GHz oscillator that is indirect optically injection-locked to a 4 GHz subharmonic frequency. This design concept could eliminate the need for switched delay-line phase shifters in the T/R modules of optically controlled phased array antennas, thus making T/R module more compact and efficient.**

I. Introduction

THE USE of a subharmonically locked local-oscillators (LO) to distribute frequency synchronization signals to remotely located T/R modules in optically controlled millimeter wave (MMW) phased array antennas is a viable approach [1]. The inherent advantages of this approach are low phase noise degradation, high AM compression, low AM/PM conversion and large locking range. Furthermore, the injection locked LO provides the opportunity to perform other functions in the same circuit, such as up/down conversion [2, [3] and phase-shifting [4], [5]. As Sturzebecher reported [3], a subharmonic optically injection locked 18 GHz oscillator can provide a precise analog phase shift of −90° to +90° with minimal phase noise degradation. However, the injection locked oscillator must be able to provide a full 360° phase shift before the complete replacement of the MMIC switched delay line phase shifters could be considered. We are presenting a novel design for a subharmonically injection locked local oscillator, consisting of two cascaded suboscillators, by which an analog phase shift over the full 360° has been achieved.

II. Design Approach of the Oscillator

A conceptual block diagram of the injection locked/phase shifter circuit is shown in Fig. 1. This circuit utilizes two cascaded suboscillators: the oscillation in each suboscillator is achieved via a transistor-based gain stage with a positive feedback through a tunable resonant tank circuit. The first suboscillator oscillates at the nth subharmonic of the oscillation frequency of the second suboscillator. The reference signal will injection-lock the first suboscillator either fundamentally or subharmonically; then the locked output from the first suboscillator will injection-lock the second suboscillator at subharmonic factor of n to generate a stable LO signal.

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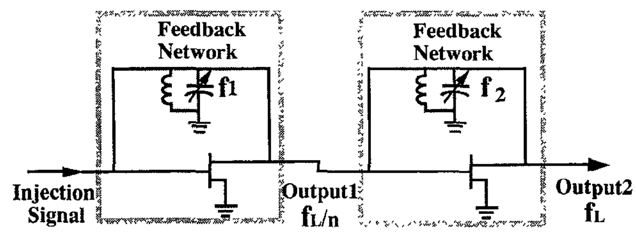

Fig. 1. Conceptual block diagram of the 360° phase shifted injection locked oscillator. f_1 and f_2 are free-running frequencies of the first and the second suboscillators, the f_L/n and f_L are locked frequencies for them where $f_1 \approx f_2/n$.

The principle of achieving phase shifting involves tuning the free running frequency of the injection-locked oscillator, as explained below. When the two cascaded suboscillators are injection locked at f_L/n and f_L, the detuning frequencies of δf_1 and δf_2 can then exist between the locked and the free-running suboscillators. The phase shift at the output of the subharmonically injection locked oscillator can be induced by detuning the free-running frequency, a phenomenon similar to that discussed by Adler [6]. This phase shift is expressed as a arcsine function of the detuning frequency [7]. More specifically, the phase shifts of the first and second suboscillators, $\Delta\phi_1$ and $\Delta\phi_2$, are

$$\Delta\phi_1 = \arcsin\left(\frac{2\delta f_1}{\Delta f_1}\right); \qquad \Delta\phi_2 = \arcsin\left(\frac{2\delta f_2}{\Delta f_2}\right). \quad (1)$$

In (1), Δf_1 and Δf_2 represent the subharmonic injection locking ranges of the two suboscillators. Clearly, maximum phase shift range of $\Delta\phi_1$ and $\Delta\phi_2$ is 190°. However, the phase shift of the first oscillator output, $\Delta\phi_1$, will be multiplied by factor of n at the second suboscillator, which is injection-locked at subharmonic factor of n [7]. Thus, for a fixed injection frequency and phase, the total phase shift at output of this LO circuit is

$$\begin{aligned}\Delta\phi_{\rm LO} &= \boldsymbol{n}\Delta\phi_1 + \Delta\phi_2\\ &= \boldsymbol{n}\arcsin\left(\frac{2\delta f_1}{\Delta f_1}\right) + \arcsin\left(\frac{2\delta f_2}{\Delta f_2}\right). \quad (2)\end{aligned}$$

Clearly, (2) shows that the available variation range of the first term is $n \times 180°$ and the second term varies over a range of 180°, if we change δf_1 and δf_2 and keep Δf_1 and Δf_2 fixed. No matter how much the second term contributes, a phase shift of over 360° for $\Delta\phi_{\rm LO}$ can always be obtained because subharmonic factor $n \geq 2$ at the second suboscillator. Therefore, we can set the phase of the output signal at any value

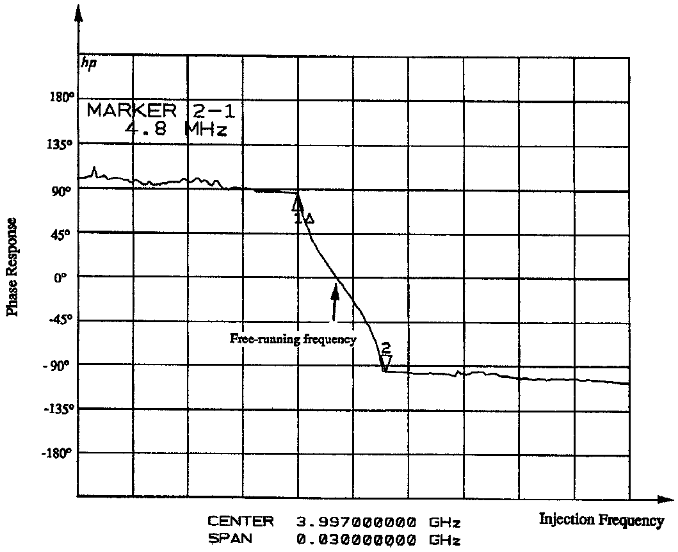

Fig. 2. Phase response at the output of the first oscillator as a function of injection frequency. The markers 1 and 2 denote the lower and upper ends of locking range. Phase response of the injection locked oscillator is the region in between. (Vertical scale is 45°/div, horizontal scale is 3 MHz/div and the center frequency is 3.997 GHz).

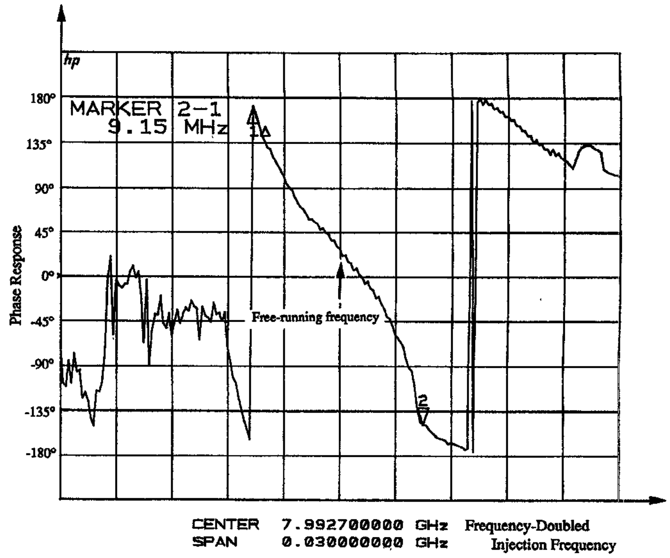

Fig. 3. Phase response at the output of the second oscillator as a function of doubled injection frequency. Markers 1 and 2 denote the lower and upper ends of locking range. The phase response of the injection locked oscillator is the region in between. (Vertical scale is 45°/div, horizontal scale is 3 MHz/div and the center frequency is 7.9927 GHz).

within 0° to 360° range by tuning the free-running frequency of the first suboscillator or that of both suboscillators. In fact, by incorporating varactor diodes into the resonant feedback circuits, we can change the free-running frequency of each suboscillator by tuning the capacitance of the diodes. This method of frequency tuning would not affect the locking range of oscillators for the constant injection signal level.

III. Experimental Results and Discussions

A local oscillator operating at 8 GHz was designed and fabricated on the basis of the structure shown in Fig. 1. Each suboscillator is a two-port oscillator constructed similarly to [8]. The oscillator consists of a single stage MESFET (NE720) amplifier, with a positive feedback. Tee-junction was used to inter-connect the output at drain to the input at the gate. The free-running frequency of the first suboscillator was about 4 GHz, and the second suboscillator was free-running at approximately 8 GHz. The cascaded oscillator was optically injection locked to a 4-GHz frequency reference signal. An AlGaAs laser diode was modulated by a 4-GHz signal from a frequency synthesizer; the modulated light was detected by a matched PIN photodiode after transmission through a 10-ft long single-mode fiber [9]. The total insertion loss of the fiber-optic (FO) link is 25 dB. The detected signal from the FO link was then injected into the first suboscillator. The locking power ratios $(P_{\text{inj}}/P_{\text{out}})$ were −35 dB and −3 dB for the first and the second suboscillators. The phase shift induced by the frequency detuning was measured through a comparison of the locked oscillator output with the frequency-doubled reference signal from the FO link in a frequency converter (HP8511A) of the HP network analyzer.

As indicated in (1), the arcsin phase-shift behavior in the range of −90° to +90° can be achieved by detuning the free-running frequency away from a fixed injection frequency. However, in our experiments, the free-running frequency was kept at a fixed value while the injection frequency was swept from 3.982 to 4.012 GHz, covering a locking range of 4.8 MHz. Both tuning methods would result in the same detuning phase behavior. Fig. 2 shows the measured phase shift of ±90° for the first suboscillator, as predicted in (1).

The output of the 4-GHz oscillator was then injected to the second-stage suboscillator to stabilize its frequency at 8 GHz. At the output of the second suboscillator, we measured a phase noise level of −84 dBc/Hz at 1 KHz offset carrier which is about 6 dB higher than the phase noise from the synthesizer. This 6-dB degradation corresponds to the theoretically expected minimum phase noise degradation $20\log(n)$ [7]. We measured the phase shift of the 8-GHz local oscillator by fixing the free-running frequencies of both suboscillators and sweeping the injection frequency to introduce the frequency detuning, as shown in Fig. 3. A phase shift of about 320° is observed over the locking range. However, the measured phase shift range is slightly less than 360° instead of being larger than 360° as described in (2).

One of the reasons for this difference is that the phase shift varies very sharply at close to the ends of locking range; a small frequency jitter of the free-running oscillator would cause a very large phase jitter [5], [7]. This sensitivity makes it difficult to measure the correct phase at large phase shift. This problem can be solved by applying dc-phase-lock-loops to stabilize the free-running frequencies of the two oscillators [3]. Another reason is the high-injection power at the second stage, the locking range Δf_2 was about 20 MHz, which is much larger than that of $2 \times \Delta f_1$. Thus, the injection locking range and the achieved phase shift of the whole circuit, represented in (2), were predominantly determined by the first stage. Also, Fig. 3 shows a 9.2-MHz locking range at 8 GHz, which is much larger than that of the common subharmonic injection locking techniques for the same injection power ratio $(P_{\text{inj}}/P_{\text{out}})$ equal to -28 dB [7].

IV. Conclusion

This novel design for subharmonically injection-locked oscillators achieves a stabilized LO source with a full 360° phase shifting capability. This design can be employed in the optically controlled phased-array antennas and antenna remoting applications [1], [10]. We demonstrated this concept by fabricating and optically synchronizing two cascaded suboscillators at 4 and 8 GHz to a 4-GHz frequency reference signal. This design can be expanded in the designing of millimeter-wave antenna front-end to perform not only frequency and phase synchronization, but also the 0°–360° phase shifting in only one local oscillator; hence, eliminating the large-space requirement for switched delay-line phase shifter in T/R modules.

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