Abstract—A subharmonically injection-locked oscillator (ILO) MMIC for local oscillators, synthesizers, and phased-array antennas is proposed. An ultrawide-band four-port active combiner/divider in the oscillator feedback loop provides an FET-oriented circuit topology extremely suitable for single-chip integration, and performs subharmonic injection locking at various subharmonic factors, \(1/n\). Two types of ILO MMIC’s were constructed. One of them exhibits a locking range as wide as 1 GHz at \(n = 1\), and the other operates at \(n\) from 1 to 16, with an output power larger than 5 dBm. The proposed ILO MMIC is promising for applications such as microwave and millimeter-wave synthesizers, large-aperture phased array antennas, frequency-selective FM receivers, and so on.

I. INTRODUCTION

OCAL oscillators play an important role in various microwave receiver and transmitter components. Using a phase-lock-loop (PLL) is a practical way to stabilize the oscillation frequency and suppress the phase noise. However, many components such as VCO’s, frequency dividers, and phase frequency comparators (PFC’s) are required, and the phase noise of the VCO has to be thoroughly suppressed beyond the PLL bandwidth. Furthermore, the frequency divider limits the stabilized oscillation frequency range, resulting in the need for additional frequency multipliers and amplifiers for higher frequencies. These requirements result in expensive, complex multichip packaging.

In this paper, a novel injection-locked oscillator (ILO) MMIC, which refers to a commercially available (or already developed) lower-frequency synthesizer IC, is proposed as an effective solution for these problems. This novel ILO MMIC is based on a two-port feedback oscillator previously reported [1] and contains an active four-port combiner/divider, instead of a passive quadrature hybrid, associated with an amplifier. The most significant advantage of the ILO is that it provides an FET-oriented circuit topology extremely suitable for single-chip integration: two in-phase active dividers are connected symmetrically at the high-impedance output ports to provide a nonreciprocal four-port combiner/divider [2]; and an amplifier is connected between an output port and an input port of the combiner/divider. The new ILO MMIC enables single-chip integration with very little increase in size and cost relative to other approaches. In addition, it makes it possible to minimize the length of the line connecting the four-port circuit and amplifier for lower effective \(Q\) of the oscillator, resulting in a wider locking range. Since the active combiner/divider operates in an ultrawide-band frequency range approaching the FET cutoff frequency, \(f_T\), injection locking to an \(n\)-th order subharmonic \((n = 1, 2, 3, \ldots)\) can be performed effectively.

The organization of this paper is as follows. First, the circuit design is outlined in Section II, with details provided on the circuit topology, free-running oscillation characteristics, and effective \(Q\). Section III describes the injection-locking ability of the proposed ILO MMIC and the characteristics of subharmonically injection-locked oscillators. Finally, possible oscillator applications are presented in Section IV.

II. CIRCUIT DESIGN

Fig. 1 shows the circuit topology for a two-port feedback oscillator, where \(A\) is the amplifier gain, and \(T\) and \(C\) are the transmission and coupling coefficients of a four-port circuit. This type of injection-locked oscillator was developed recently by Birkeland and Itoh [1] for space power combining. It was shown to have a wide injection-locking range due to its low effective \(Q, Q_{eff}\), which is represented as

\[
Q_{eff} = \frac{B|C|\omega_0}{2T^2},
\]

where \(B\) is the rate of change of phase \(AC\) at the free-running oscillation frequency, \(\omega_0\). The effective \(Q\) of an oscillator is based on its open-loop frequency characteristics [3]. However, the oscillator designed by Birkeland and Itoh uses a passive quadrature hybrid for the four-port circuit, and thus is applicable only to fundamental-frequency injection signals.

Fig. 2 shows an active combiner/divider replacement for the passive quadrature hybrid for \(n\)-th order subharmonic locking. As the figure shows, it consists of two in-phase dividers, each of which has a pair of symmetrical common-gate-FET’s (CGF’s), connected to each other at the high-impedance output ports to provide a non-reciprocal 4-port circuit. The input ports \(1\) and \(2\) and the output ports \(3\) and \(4\) are isolated from each other, respectively, and every input port-output port path is nonreciprocal due to the unilateral characteristic.
of the CGF's. The advantage of the module is that there is very little phase change in it. The rate of phase change from input port to output port was measured and found to be merely 5 GHz. The nonreciprocal four-port combiner/divider in the LUFET form [Fig. 2(b)] operates in an ultrawideband frequency range reaching the FET cutoff frequency, \( f_{\text{r}} \). The frequency responses of the combined/divider are shown in Fig. 3. The transmission and coupling coefficients are 5–6 dB, and port isolations are greater than 20 dB below 20 GHz. The amplifier gain required is larger than 6 dB, which is easily obtained in various frequency bands and can be found in circuit libraries. Therefore, the ultrawide-band performance is extremely suitable for injecting various orders of subharmonics.

Two ILO MMIC's were implemented and are described in this paper. The fundamental part for subharmonic injection locking is the same for both circuits, while the input amplifier is designed according to the purpose for which the circuit is intended. The active combiner/divider and loop amplifier are connected through 50 \( \Omega \) lines to adjust the oscillation frequency, with the shortest line length used to minimize the rate of change of the open-loop phase. The contribution of the line to the \( Q_{\text{eff}} \) is less than one-half that of the amplifier.

A. Free-Running Oscillation

This subsection describes the ILO's behavior before reaching free-running oscillation and the phase-frequency characteristics in the oscillation loop. Fig. 4 shows an injection-locked oscillator MMIC and its circuit scheme including the dc bias circuitry. The circuits have a uniplanar configuration and the chip is 2 x 4 mm. A 0.1–20 GHz active combiner/divider in the center and a 3.5–7 GHz variable gain amplifier on the right are combined so as to make the phase shift in the loop 360° at a 6-GHz-band frequency, thereby providing a 6-GHz band two port oscillator. The total length of the lines that connect the combiner/divider and the amplifier is 3.72 mm. The 3.5–7 GHz 10-dB-gain amplifier on the left is the same as the one on the right, except for the latter's gain control terminal, \( V_{\text{CONT}} \), and the former's amplification of the incident signal. These amplifiers were not specifically designed for this MMIC but were developed as local amplifiers for a mixer module. The saturation output power of the amplifiers is over 13 dBm. The bias circuitry for the combiner/divider was designed so as not to change the amplifier frequency characteristics. The ILO MMIC operates at 5 V and 100 mA.

The incident signal to the input port, \( I_N \), is amplified 10 dB by a 3.5–7 GHz buffer amplifier, divided at one of the combiner/divider input ports, delivered to the combiner/divider output ports, and then one of the signals is amplified through the variable-gain amplifier. The amplified signal is again divided at the other input port of the combiner/divider: one is fed back to the variable-gain amplifier input port, forming a closed loop; and the other one comes out from the ILO MMIC output port, \( O_U \). The output signal is already amplified by the loop gain, and therefore the gain-frequency response from the ILO MMIC input to output is closely related to the loop gain.

By controlling the gain of the 3.5–7 GHz amplifier on the right, as shown in Fig. 5, the oscillation-loop gain increases toward free-running oscillation. Fig. 6(a) and (b) shows the frequency response of the gain and phase, respectively, from the ILO MMIC input to output. The loop gain is stable and low when \( V_{\text{CONT}} \) is below –1 V, where the amplifier gain is 0 dB. It increases rapidly at 5.73 GHz with increasing control voltage, and reaches free-running oscillation at \( V_{\text{CONT}} \) over 0.1 V. The amplifier gain is about 7 dB at the control voltage, which is a little larger than 6 dB to compensate for the loss of
the lines and bias circuits in the loop. The phase in the closed loop at a $V_{\text{CONT}}$ of 0.1 V shifts quickly around the resonant frequency. This caused by the closed-loop filtering effect. The amplifier is finally biased at a $V_{\text{CONT}}$ of 2.5 V with a gain over 10 dB insensitive to the changes in control voltage.

Fig. 7 shows the free-running oscillation spectrum. The spectrum is as wide as 400 kHz, and it predicts that the feedback oscillator has a very low $Q$ compared to the reflection type. This feature is a great advantage for wide-band injection locking.

The excess phase of about 40° observed at 5.73 GHz is caused by such factors as the 320° phase shift in the buffer amplifier, the CGF in the combiner/divider, and the lines between them. The phase-change rate of the circuitry, which is derived from the phase-curve for a $V_{\text{CONT}}$ of -3 V, is 56°/GHz. By eliminating the lines’ contributions to the above data, a phase shift of 290° and a phase-change rate of 50°/GHz for the amplifier and CGF in the oscillation loop are obtained. This is because the oscillation frequency is merely 5 MHz lower than the frequency at the cross point in Fig. 6(b).

B. Effective $Q$

The injection-locking bandwidth of a feedback oscillator of this type can be estimated by means of its open-loop frequency characteristics. The analysis procedure described in [1] confirmed that equation (1) was applicable to the proposed ILO with the active combiner/divider. In as much as $T$ and $C$ are 0.5 and $B$ is the summation of the phase-change rates of the variable-gain amplifier, CGF, and the lines connecting them, the above equation is rewritten for the proposed ILO as:

$$Q_{\text{eff}} = \frac{\omega_0}{d\omega} \left[ \theta_A(\omega) + \theta_L(\omega) \right]$$

(2)

where $\theta_A(\omega)$ indicates the total phase shift in the amplifier and CGF, and $\theta_L(\omega)$ indicates that in the lines. The phase shift $\theta_A(\omega)$ is derived as:

$$\theta_A = \frac{290^\circ}{5.73} f(\text{GHz})$$

(3)
TABLE I
FREE-RUNNING OSCILLATION FREQUENCIES AND ESTIMATED EFFECTIVE Q’S FOR THE ILO’S

<table>
<thead>
<tr>
<th>ILO Frequency (GHz)</th>
<th>Oscillation freq.</th>
<th>Line Length</th>
<th>Q_{eff}</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-GHz ILO</td>
<td>4.402</td>
<td>11.0 mm</td>
<td>6.24</td>
</tr>
<tr>
<td>5-GHz ILO</td>
<td>5.089</td>
<td>6.46 mm</td>
<td>6.09</td>
</tr>
<tr>
<td>6-GHz ILO</td>
<td>5.722</td>
<td>3.72 mm</td>
<td>6.09</td>
</tr>
</tbody>
</table>

Fig. 8. Injection-locked oscillation spectra at the center and edges of the locking range. Injection power level is 0 dBm.

from the data obtained above. Using (2) and (3), and the $Q_{eff}$ of fabricated 4-, 5-, and 6-GHz ILO MMIC’s are estimated as shown in Table I.

The line for the 4-GHz ILO is a capacitor-loaded high-impedance line for chip-size saving, and is replaced with an equivalent 50 Ω line in the estimation. As a result, the $Q_{eff}$ of the proposed ILO is as low as 6. Although the values are about twice those of a quadrature-hybrid type due to the smaller $T$ value, the 10-dB gain of the integrated buffer amplifier easily compensates for such minor differences.

III. SUBHARMONICALLY INJECTION-LOCKED OSCILLATORS

The locking ranges at various incident power levels of the ILO MMIC in Fig. 4 were measured to evaluate the injection-locking ability of the proposed ILO MMIC. The locking range edges were measured by detecting the unlocking spectrum. Fig. 8 shows the locked spectrum at the center and edges of the locking range when the incident power at the MMIC input port is 0 dBm. The locking range is about 1 GHz and the output power is over 5 dBm. The oscillation power in the loop is estimated as being over 10 dBm because it is divided by the combiner/divider with a 6 dB loss. Fig. 9 shows the measured locking ranges for the subharmonic factors, $1/n$ of 1 and 1/2. The locking range at $n = 1$ is as wide as that reported in [1], in which a quadrature hybrid was used for signal injection designed for $n = 1$. The subharmonic injection locking at $n = 2$ increases sharply above 0 dBm incident power. The considered reason is that the buffer amplifier generates a large second harmonic, which exceeds that in the oscillation loop, near and in the amplifier saturation. The measurements confirm that the injection locking ability is high enough to achieve further subharmonic lockings in reasonable locking ranges.

Fig. 9. Measured locking ranges for the fundamental and the second subharmonic.

Injection-locked oscillators which have the free-running oscillation frequencies listed in Table I, and which operate at subharmonic factors reaching 1/16, have been designed and fabricated. The circuit scheme and MMIC photographs of these oscillators are shown in Figs. 10 and 11. The input 3.5–7 GHz buffer amplifier in Fig. 4 is replaced with a 0.3–2 GHz 15-dB-gain amplifier [4], thereby significantly improving the incident signal frequency range and the locking ability. The amplifier is designed to degrade the gain gradually beyond 2 GHz. The gain-frequency response enhances the locking ability at a larger $n$. This circuit scheme, consisting of a common-gate FET and resistor-loaded gain blocks, is shown to have the desired performance level. The saturated output power of the amplifier is over 3 dBm below 2 GHz when the ILO MMIC’s are used at 5 V/−5 V and 130 mA, and a little larger beyond 2 GHz due to the gain slope.

As an example of the ILO MMIC’s performance, measured locking range versus incident power characteristics of the 5-GHz ILO MMIC for $n$ of 1, 2, and 4 are shown in Fig. 12(a). Each locking range is nearly constant above an incident power of 5 dBm due to the injection-power saturation. The locking-range change for the incident-power level from −10 dBm to 0 dBm, which saturates the amplifier for $n$ larger than 2, indicates that the locking range is determined by the nonlinearity not only for the oscillation loop but also for the
buffer amplifier. The locking range versus $n$ characteristics for the incident power of 0 dBm are shown in Fig. 12(b) for the 4-, 5-, and 6-GHz ILO MMIC's. Injection locking at subharmonic factors reaching $1/16$ has been obtained.

The typical locking ranges at $n = 1, 2, \text{and} 4$ are summarized in Table II. The oscillation output power is over 5 dBm for each $n$ [4], and large enough for pumping mixers. At the incident power level of 0 dBm, the locking range, $W_n$, for the subharmonic factor, $1/n$, is roughly represented according to the measured curves around the dotted line as

$$W_n/W_1 = (1/n)^{1.3}.$$

The smaller the value of the superscript, the wider the subharmonic locking range. For an incident power of $-5$ dBm, the value was observed to increase. Such extended injection locking is possible with the ultrawide-band combiner/divider, and the ability is enhanced by the input buffer amplifier characteristics.

The phase-noise increase at the $n$th-order subharmonic should be low enough for local oscillator applications, that is, it should not exceed those of frequency multipliers. A phase noise characteristic at $n$ of 4 is, for example, shown in Fig. 13 compared to that of the injection signal source, HP 8673D. The signal source puts a signal with one-quarter of the oscillation frequency into the ILO MMIC. The difference between the curves indicates the phase-noise increase from the subharmonic locking. The phase-noise characteristics of the 4-GHz band ILO MMIC for various orders of subharmonics are summarized in Fig. 14. In the figure, the phase-noise increase in decibels for each $n$ is added to the phase noise for the fundamental injection locking ($n = 1$). The degradation rate is very close to 6 dB/oct at each off-carrier frequency, which is the same as that of a frequency multiplier, and is a predicted ILO noise behavior in [5].
These results mean that the subharmonically injection-locked oscillator is comparable to frequency multipliers in phase noise, and provides additional amplification of the output power, significantly simplifying the configuration of local oscillators and synthesizers in microwave and millimeter-wave regions.

IV. APPLICATIONS

The ILO MMIC has great potential to advance the space power combining technique, as well as to simplify local oscillators and frequency converters. Fig. 15 shows an oscillator array using the ILO MMIC’s. The ILO MMIC’s and phase shifters are connected sequentially through the input ports and monitoring ports. The input signal locks the ILO MMIC’s at the same oscillation frequency, and provides each oscillator with a specific oscillation phase that is provided by the path to the oscillator. The number of ILO MMIC’s can be increased independently of the oscillator allocations because the three ports of the ILO MMIC are isolated from the others. The signal for injection locking goes straight forward and the oscillation power comes out in parallel. The injection signal frequency can be much lower than the oscillation frequency. These features provide for a flexible allocation of the oscillator output ports to the paths which feed the injection signal, and permit us to eliminate the n-way RF power divider used in [1], and the precise adjustment of line lengths required in [6]. Furthermore, some of the ILO’s in Fig. 15 can be turned off without any damage to the other ILO’s and the feeding paths by controlling only the amplifier gain in the oscillation loop. It is useful to operate the array at different frequencies and in different beam forms.

Other applications considered are described briefly below. It should be relatively easy to develop a large-aperture phased array antenna with transmit/receive (T/R) modules synchronizing to a reference signal from a central control unit or by a fiber-optic link, and a frequency-selective (or adaptive) FM receiver utilizing a locking effect that enhances a signal in the center of the locking range and suppresses the others. The proposed ILO MMIC can be functionally enhanced by using a voltage-controllable delay line: a combination of a line and varactor diodes, that makes the above applications more flexible. The ILO MMIC integrated with a mixer MMIC in a miniature package can be a low-cost signal processing unit for array antennas, multiphase/amplitude modulators, because it allows lossy and extremely simplified n-port phase splitters.

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REFERENCES

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