Injection-Locked Oscillator Chain: A Possible Solution to Millimeter-Wave MMIC Synthesizers

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***Abstract*— An injection-locked oscillator (ILO) monolithic-microwave integrated-circuit (MMIC) chain—a cascade of low- and high-frequency-band ILO's—is proposed for simple and cost-effective millimeter-wave local oscillators and synthesizers. Primary 5-, 20-, and 50-GHz-band ILO MMIC's are designed and fabricated as an ILO-chain chip set. Improvements made to the active combiner/dividers (A-C/D's), the heart of the MMIC, in the external feedback path for an amplifier to suppress spurs at the output port of 5- and 20-GHz-band ILO's, and enhance the loop gain and layout flexibility at millimeter-wave frequencies. Fabricated 5- and 20-GHz-band ILO MMIC's are chain-connected to confirm the design techniques. The ILO chain provides a 20-GHz-band output signal for an injection signal of 571 MHz, as well as a very low level of spurs of less than −45 dBc around the output signal. The measured results show that the proposed ILO chain is extremely suitable for developing full millimeter-wave MMIC frequency synthesizers.**

***Index Terms*—Frequency synthesizer, injection-locked oscillator, millimeter wave, MMIC oscillator, subharmonic.**

I. Introduction

MILLIMETER-WAVE system applications such as wireless local area network (LAN) and mobile satellite-communication systems are rapidly expanding, and several millimeter-wave sources using dielectric resonator oscillators (DRO's) and phase-locked oscillators (PLO's) have been reported [1]–[4]. PLO's are more suitable for monolithic-microwave integrated-circuit (MMIC) implementation and synthesizer development than DRO's. However, PLO's contain many components such as voltage-controlled oscillators (VCO's), frequency dividers, and phase/frequency comparators (PFC's), resulting in a high cost due to complex multichip packaging. Furthermore, they need additional frequency multipliers and amplifiers at millimeter-wave frequencies because of the operation frequency limitation of frequency dividers. The frequency multipliers require an expensive RF filter at the output port, so serious difficulties arise when realizing full monolithic synthesizers.

This paper proposes a subharmonic injection-locked oscillator (ILO) MMIC chain [5], which uses a commercially available lower frequency synthesizer—IC—to solve the above problems. The ILO chain cascades low- and high-frequency-band ILO's to multiply the reference by $n \times m$ (n, m: integers larger than 2) using two chips. This ILO chain has a configuration similar to that previously reported by Zhang and Daryoush [6]–[8]. However, the emphasis of our ILO chain is to achieve much higher multiplication ratio than that of Zhang's, which was designed for a full 360° phase shift. Additionally, the ILO chain suppresses adjacent spurs at higher multiplication levels due to the enhancer effect of the second ILO.

Primary 5-, 20, and 50-GHz-band ILO MMIC's are designed and fabricated as an ILO-chain chip set. Each ILO MMIC is simply constructed with an active combiner/divider (A-C/D), a loop amplifier with an adequate delay line, and an input buffer amplifier. The A-C/D's are designed so that they meet all operation requirements. The 5- and 20-GHz-band A-C/D's are nonreciprocal six-port circuits that suppress spurs from the output port, and the 50-GHz-band A-C/D employs low-impedance lines at the output ports to enhance the loop gain and layout flexibility at millimeter-wave frequencies.

The 5- and 20-GHz-band ILO MMIC's exhibit output spectra with spurs as low as −30 dBc for subharmonic factors, with n of more than 3. In addition, the ILO's also perform subharmonic ILO at subharmonic factors of 1/16 and 1/32. The 50-GHz-band ILO MMIC shows injection-locking ability at subharmonic factors from 1 to 1/4 without a buffer amplifier. Finally, the 5- and 20-GHz-band MMIC ILO's are chain connected and tested. The MMIC ILO chain offers a pure output signal with very low spur levels of less than −45 dBc around the output signal for an injection signal of 571 MHz. This result means that the ILO-chain configuration does not require any RF filters at the output port. Thus, the subharmonic ILO–MMIC chain is extremely suitable for building simple and low-cost full-monolithic millimeter-wave frequency sources and frequency synthesizers. Finally, the estimation of phase-noise characteristic shows that the ILO-chain is a powerful tool to realize low phase-noise oscillators at high frequencies.

II. ILO Chain Concept and Design

The most significant advantage of the ILO MMIC is its simple configuration: an A-C/D is combined with a loop amplifier with an adequate delay line [9]–[12], as shown in Fig. 1. In addition, its phase-noise characteristic depends on the injection signal purity, and the degradation rate against the subharmonic factor is very close to 6 dB/octave, the same as that of frequency multipliers [9]. Furthermore, the ILO MMIC exhibits a wide locking range even at subharmonic factors $1/n$ of under 1/2, i.e., 1/16 or less, with the aid of an input buffer amplifier, which allows us to eliminate additional frequency multipliers and amplifiers. As shown in Fig. 2, this results in two-chip or one-chip integration for very high levels

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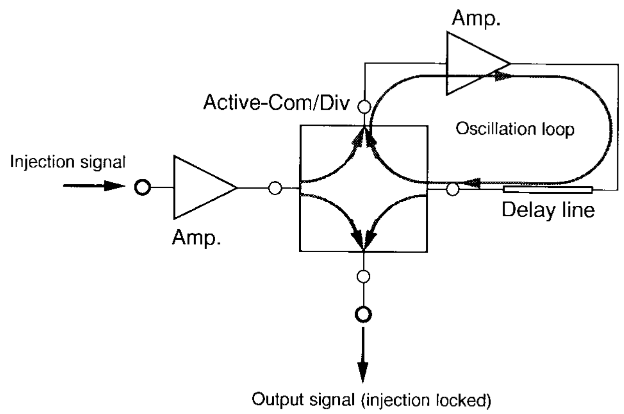


Fig. 1. Circuit topology of the ILO.

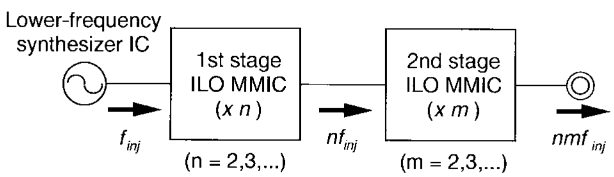


Fig. 2. Configuration of the ILO–MMIC chain.

of multiplication $(n \times m)$ of the reference signal frequency f_{inj}. Therefore, a subharmonic ILO chain, a cascade of low-, high-frequency-band ILO's, is a candidate for millimeter-wave MMIC oscillators and synthesizers; the ILO–MMIC chain can use a commercially available (or already developed) synthesizer IC to provide a reference signal around or below 1 GHz.

The important design issues for the ILO chain are: 1) the suppression of spurs from the output port of the first-stage ILO to achieve stable second-stage operation and obtain a pure output spectrum in the millimeter-wave region; 2) how to provide enough loop gain for the second-stage ILO despite the performance degradation of the millimeter-wave amplifier; and 3) how to achieve effective loop layout even with short delay lines. For these issues, each A-C/D's—the heart of the MMIC—implemented in the external feedback path for an amplifier is improved to complete the design of an ILO-chain MMIC chip set.

A. First-Stage ILO

The first-stage ILO MMIC (see Fig. 2) must provide a pure output signal for injection into the second-stage ILO. Conventional ILO's use a four-port A-C/D and suffer leakage of the injection signal and its harmonics from the injection signal input port to the output port if an output filter is not used. The circuit scheme and signal flow for the newly designed first-stage ILO MMIC is shown in Fig. 3. The six-port A-C/D, which consists of three active in-phase dividers [a pair of common-gate FET's (CGF's)] connected to one another through their high impedance output ports, effectively solves the problem of leakage [13]. The six-port A-C/D suppresses spurs from the output port because the third in-phase divider prevents signal flow between the input and output ports.

The signal injected into the input port IN is amplified by the buffer amplifier, divided at the input port ① of the A-C/D, delivered to the output ports ② and ⑥, and the output signal

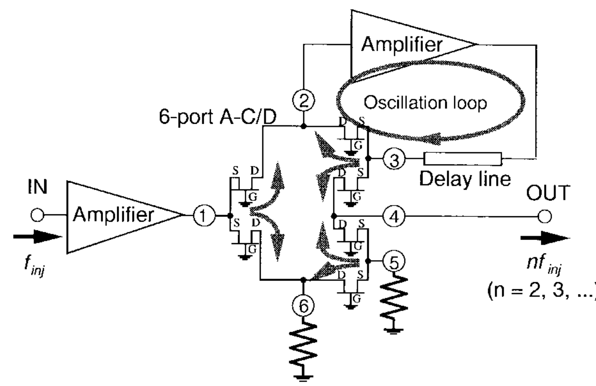


Fig. 3. Circuit scheme of the first-stage ILO.

at port ② is amplified in the loop amplifier. The amplified signal is again divided at the input port ③ of the A-C/D: one of the divided signals is fed back to the loop amplifier input port, forming a closed loop, and the other one exits from the ILO MMIC output port ④ OUT. The signal delivered to port ⑥ is terminated with a 50-Ω load, and so does not appear at output port ④ [14].

B. Second-Stage ILO

The circuit scheme and the signal flow of the second-stage—ILO millimeter-wave operation—is shown in Fig. 4(a). As the frequency increases, the coupling gain of the A-C/D gradually decreases as shown by the curve "conventional" in Fig. 4(b). This makes it very difficult to achieve enough loop gain and margin because loop amplifier gain also decreases at millimeter-wave frequencies. Furthermore, the short delay lines needed by the high frequency causes layout mismatch in connecting the A-C/D and the loop amplifier. Placing low-impedance lines at the output ports enhances the coupling gain at operation frequencies because these lines work as impedance transformers. The effect for 20- and 35-Ω lines with lengths of 650- and 520 μm, respectively, is shown in Fig. 4(b). Up to 5-dB improvement in gain is possible at 50 GHz by lowering the impedance. In addition, these lines ease the difficulty of pattern layout at higher frequencies.

C. Implementation of ILO's

5-, 20-, and 50-GHz-band ILO MMIC's were designed and fabricated. The 5- and 50-GHz-band ILO's were used as the first and second stage, respectively. The 20-GHz-band ILO can be used as both.

III. ILO MMIC Performance

A. 5-GHz-Band ILO

Fig. 5 is a photograph of the 5-GHz-band ILO MMIC, which uses 0.3-μm MESFET's. The chip size is 1.8 $\times$ 3.8 mm^2. The ILO MMIC operates at 5 V/$-$5 V and 150 mA. The six-port A-C/D and the 3.5–7 GHz 10-dB-gain loop amplifier combine to realize a 360° phase shift in the loop in the 5-GHz band. The effective Q, Q_{eff}, of the 5-GHz-band ILO MMIC is estimated to be 6.26 by the procedure of Birkeland and Itoh [15] and the procedure described in [9]. The 0.3–2-GHz 15-dB-gain buffer amplifier [10] was designed to degrade the gain

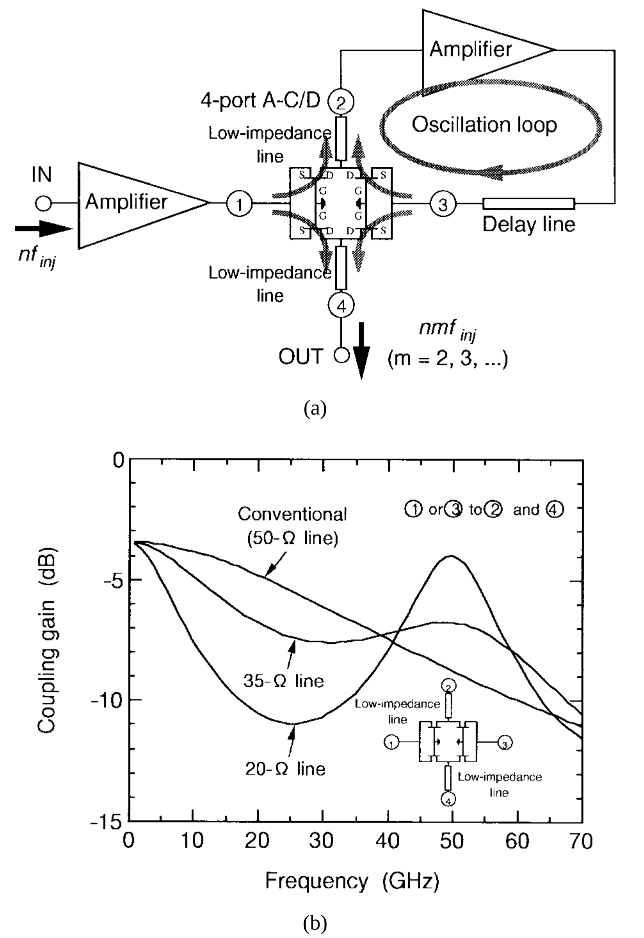


Fig. 4. (a) Circuit scheme of the second-stage ILO. (b) Calculated performance of the A-C/D.

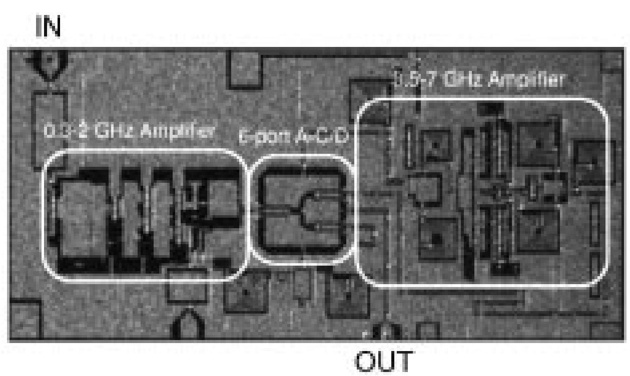


Fig. 5. Photograph of the 5-GHz-band ILO MMIC (chip size: 1.8 × 3.8 mm).

gradually beyond 2 GHz in order to enhance the locking ability at higher order subharmonics. Measured injection-locking-range characteristic of this ILO for subharmonic factors of $1/n$ from 1 to 1/16, is shown in Fig. 6, and is similar to that of the conventional ILO [9]. The oscillation output power is over 7 dBm for each n. Fig. 7 compares the normalized output spectra of a fabricated 5-GHz-band ILO MMIC and a conventional one for an eighth subharmonic signal. Since signal leakage from input port ① to output port ④ is suppressed due to the six-port A-C/D structure up to the FET cutoff frequency and simple LC filter at the output port, the levels of undesired out-

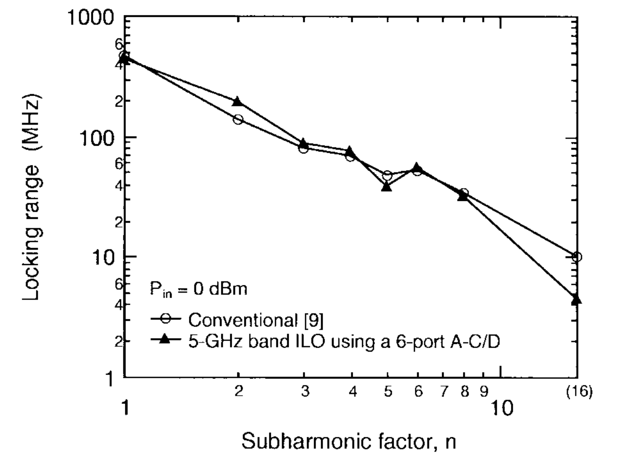


Fig. 6. Measured injection-locking range of the 5-GHz-band ILO MMIC versus n.

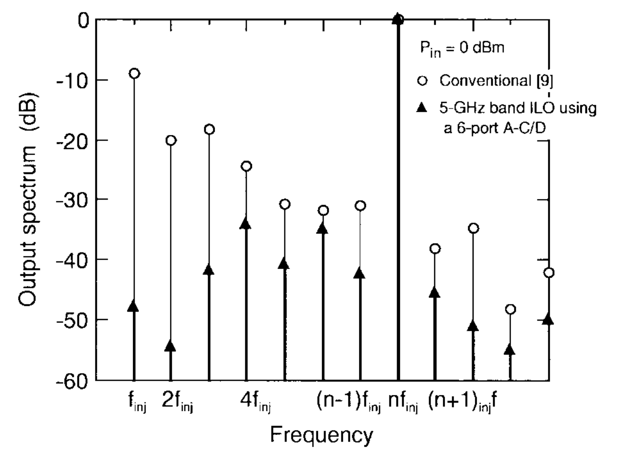
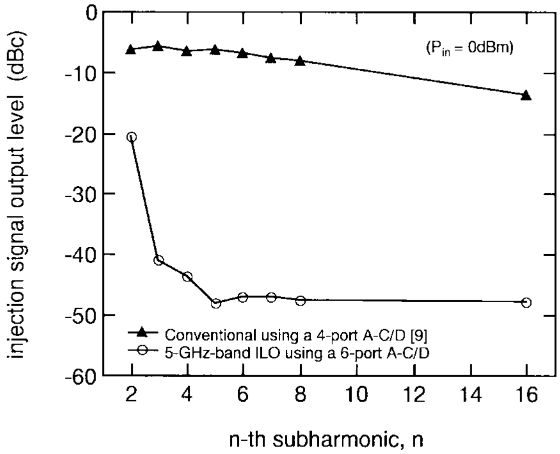


Fig. 7. Comparison of measured injection-locking range characteristic of the 5-GHz-band ILO using a six-port combiner/divider and a conventional ILO using a four-port combiner/divider [9]: eighth subharmonic.

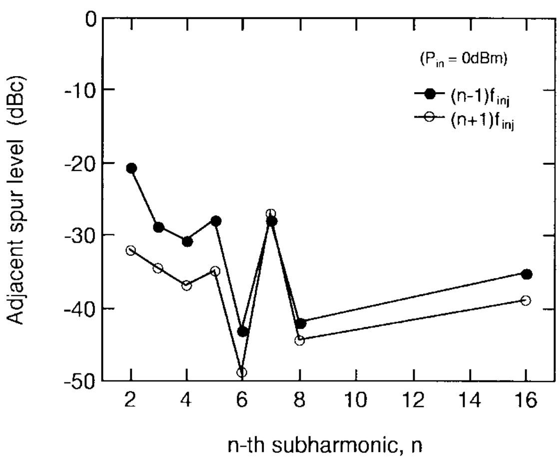
put signals are less than −34 dBc. Especial noteworthy is that the level of the injection signal and that of its second harmonic generated in the buffer amplifier are reduced by more than 30 dB compared to that of a conventional ILO with a four-port A-C/D and no output filter. Fig. 8(a) and (b) indicate measured output spur levels $f_{\rm inj}$ and $(n \pm 1)f_{\rm inj}$, respectively, for each subharmonic factor. The 5-GHz-band ILO achieves an injection signal suppression of more than 40 dB, as well as an adjacent spur level as low as −30 dBc for all subharmonic factors.

B. 20-GHz-Band ILO

Fig. 9 shows a photograph of the fabricated 20-GHz-band ILO MMIC, which uses 0.2-μm AlGaAs/InGaAs/GaAs high electron-mobility transistors (HEMT's) with 0.75-dB minimum noise figure at 18 GHz. The chip size is 1.4 × 1.4 mm^2. The ILO MMIC operates at 6 V/2 V/−2 V and 100 mA. The 14–24-GHz 10-dB-gain loop amplifier and the six-port A-C/D combine to realize a 720° phase shift in the 20-GHz band. The delay-line length totals 3 mm, 170° at 20 GHz, and the $Q_{\rm eff}$ of 20-GHz-band ILO MMIC is 10.56. The 0.3-5-GHz input buffer amplifier is located on the upper left. The characteristics of the buffer and loop amplifier are shown in Fig. 10(a) and (b). The 0.3–5 GHz 20-dB-gain buffer



(a)



(b)

Fig. 8. The spur levels of signal output by the 5-GHz-band ILO MMIC. (a) Injection signal $f_{\rm inj}$. (b) Adjacent signal $(n \pm 1) f_{\rm inj}$.

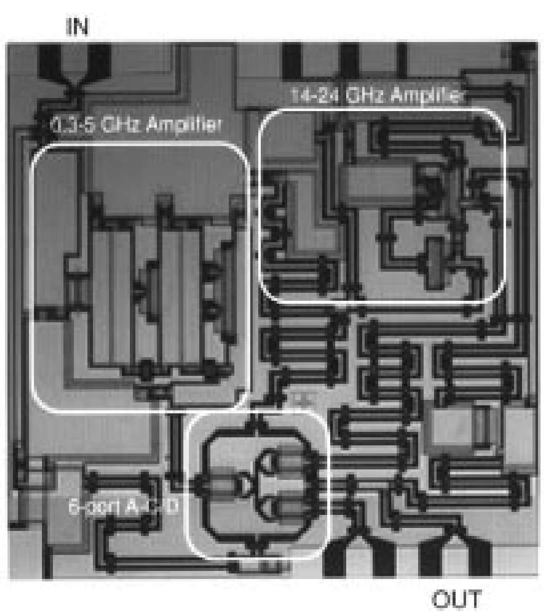
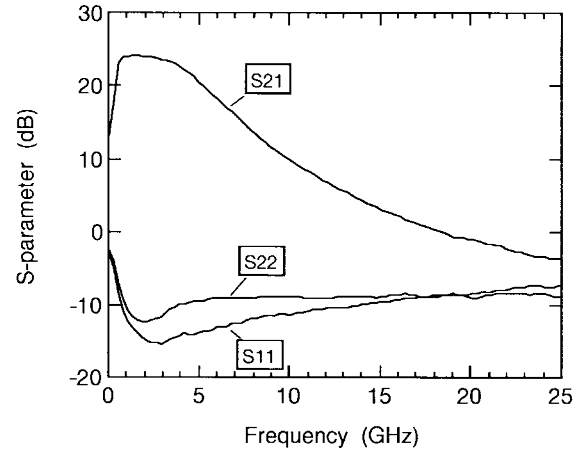
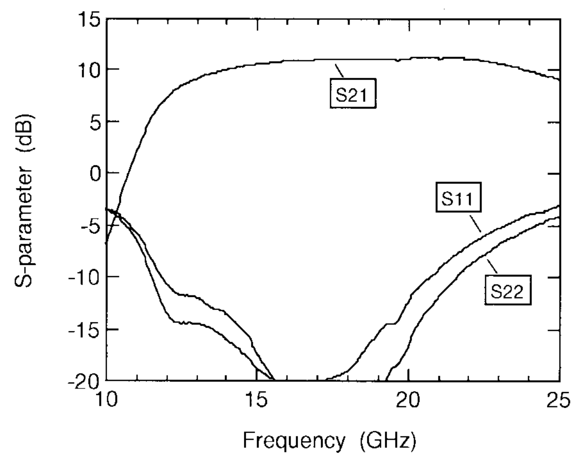


Fig. 9. Photograph of the 20-GHz-band ILO MMIC (chip size: 1.4 × 1.4 mm).



(a)



(b)

Fig. 10. Characteristics of the buffer and loop amplifier of the 20-GHz-band ILO MMIC. (a) Buffer amplifier. (b) Loop amplifier.

amplifier was designed to degrade the gain gradually beyond 5 GHz, as shown in Fig. 10(a), which increases the injection-locking ability at higher order subharmonics. The saturated output power of the buffer amplifier is 0 dBm at 20 GHz. The locking range versus n characteristics for the injection signal power of 0 and 10 dBm are shown in Fig. 11. This 20-GHz-band ILO locks even to the 32nd subharmonic signal for an injection power of 10 dBm. For an injection power of 0 dBm, the locking range for the fourth subharmonic is wider than those of the fundamental and second subharmonic. This is due to the frequency and saturated power characteristics of the buffer amplifier. The ratio of the flat-gain frequency band to the ILO's output frequency is nearly 50% smaller than that of the 5-GHz-band ILO, and the saturated output power of the buffer amplifier for the 5-GHz-band ILO is 7 dBm at 5 GHz. These are the origin of the locking-range characteristic versus subharmonic factor n. The fact that the locking-range increases at $n = 4$ can be effectively used to create a MMIC–ILO chain. The oscillation output power, which depends on loop amplifier's saturated output power, is larger than 2 dBm for all values of n considered.

C. 50-GHz-Band ILO

Fig. 12 shows a photograph of the fabricated 50-GHz-band ILO MMIC which uses 0.1-μm pseudomorphic AlGaAs/InGaAs/GaAs HEMT's with the 2-dB minimum noise

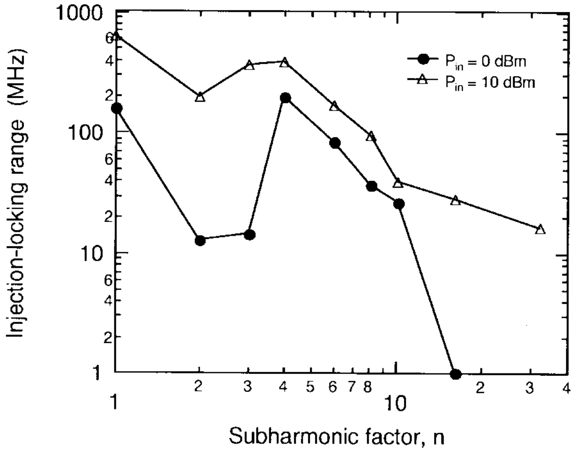


Fig. 11. Measured injection-locking range of the 20-GHz-band ILO MMIC versus subharmonic factor n.

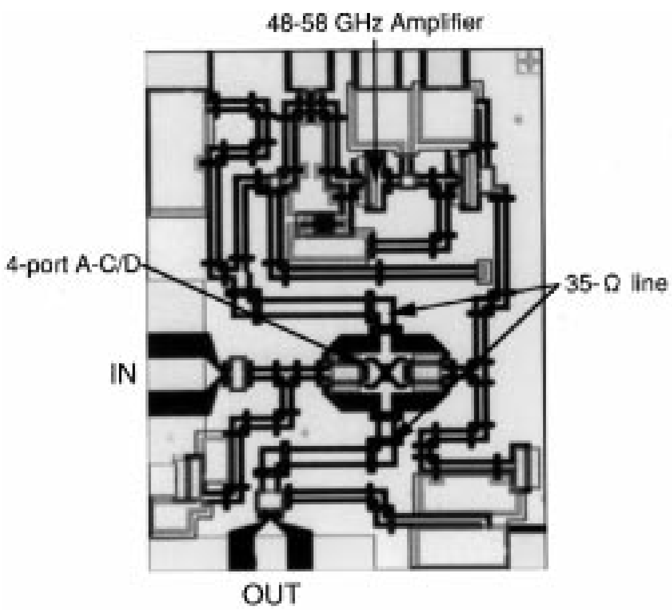


Fig. 12. Photograph of the 50-GHz-band ILO MMIC (chip size: 1.2 × 0.9 mm).

figure at 60 GHz. The chip size is only 1.2 × 0.9 mm^2. The ILO MMIC operates at 1.5 V and 35 mA. The four-port A-C/D with low-impedance lines at the output ports and the 48–58 GHz 10-dB-gain loop amplifier combine to realize a 720° phase shift in the loop in the 50 GHz band. The 35-Ω low-impedance lines connected to the output ports are 0.52-mm long, and the delay line length is 0.7 mm, or 80°. The $Q_{\rm eff}$ of the 50-GHz-band ILO MMIC is estimated to be 12.56. The loop amplifier was designed for the two-stage scheme. The performance of the loop amplifier, which occupies only 0.55 × 0.45 mm^2 of the ILO chip is shown in Fig. 13. Amplifier performance, defined as gain-bandwidth product per chip size (mm^2) is the best yet reported for millimeter-wave amplifiers [16], [17]. Amplifiers this small offer a considerable benefit in ILO layout design. The 50-GHz-band MMIC ILO, as shown in Figs. 14 and 15, can be injection-locked for subharmonic factors $1/m$ for m from 1 to 1/4 without a buffer amplifier, for the injection signal power of 5 dBm. The oscillation output power from the ILO MMIC is larger than −5 dBm for each

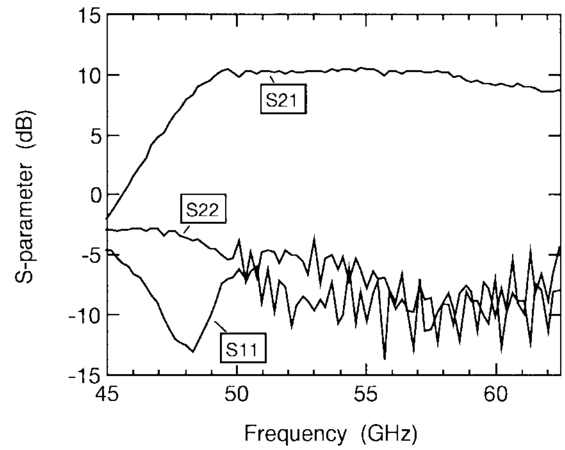


Fig. 13. Performance of the loop amplifier in the 50-GHz-band ILO MMIC.

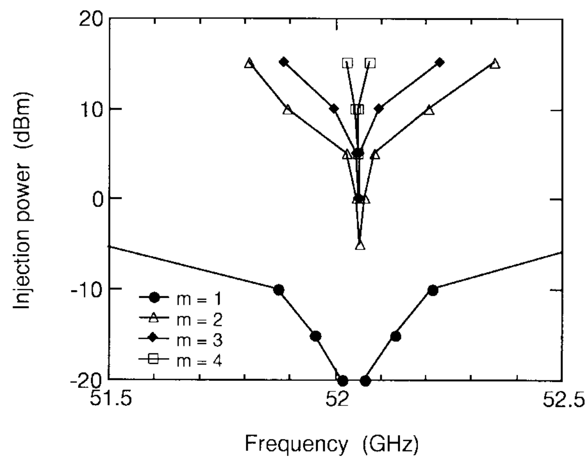


Fig. 14. Measured injection-locking range of the 50-GHz-band ILO MMIC versus injection power.

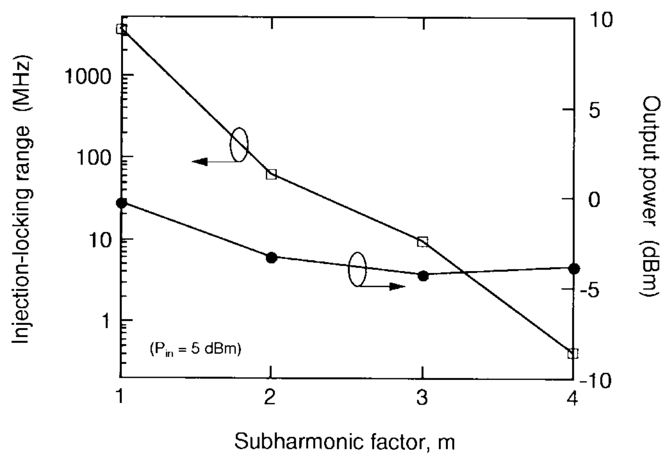


Fig. 15. Measured injection locking range and oscillation output power of the 50-GHz-band ILO MMIC versus subharmonic factor m.

m value, as shown in Fig. 15. Using a buffer amplifier whose gain-frequency characteristic is similar to that in Fig. 10(a) greatly improves the locking range for higher values of m.

IV. An Experimental ILO Chain

An experimental ILO chain was constructed using the fabricated 5-GHz-band and 20-GHz-band ILO MMIC's. Fig. 16

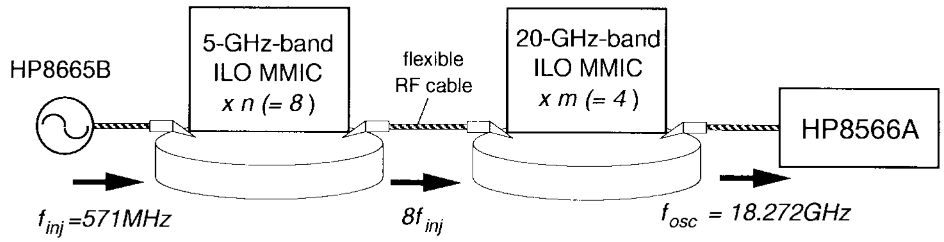


Fig. 16. Measurement setup for the 5- and 20-GHz-band ILO–MMIC chain.

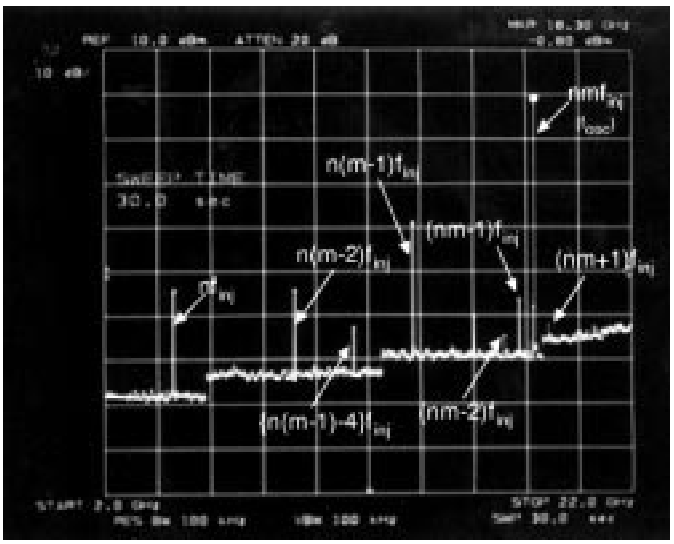


Fig. 17. Output spectra of the 5- and 20-GHz-band ILO chain.

shows the setup for output spectra measurement. Each MMIC was set on a Cascade Microtech RF probe station, and the output port of the 5-GHz-band ILO was connected with flexible microwave cable to the input port of 20-GHz-band ILO. Subharmonic factors n and m were set at 8 and 4, respectively, considering the injection-locking characteristics shown in Fig. 11 as well as Fig. 6. An HP 8665B was used as the injection signal source and the output spectrum of the 5- and 20-GHz ILO chain was measured by an HP 8566A. Fig. 17 shows the output spectra from the 5- and 20-GHz ILO chain when the reference signal of 571 MHz was injected into the 5-GHz-band ILO's input port. The value of multiplication $nm = 32$ for each spur is also shown in the figure. The 5-GHz-band ILO was locked at 4.568 GHz and the 20-GHz-band ILO at 18.272 GHz. The 5- and 20-GHz-band ILO chain exhibited adjacent spur levels $(nm \pm 1) f_{\rm inj}$ as low as −45 dBc at the output port. The adjacent spurs are suppressed well due to the enhancer effect of the 20-GHz-band ILO MMIC. The highest measured spur level, $m(n-1) f_{\rm inj}$ (13.704 GHz), was −28 dBc; however, it can be easily suppressed by a simple *LC* filter because the frequency separation from the desired output signal frequency (18.272 GHz) is 4.568 GHz, i.e., 25% offset. This means the ILO chain renders it unnecessary to add expensive RF filters at the output port. It is clear that the ILO chain is useful for millimeter-wave frequency operation as well as the 5- and 20-GHz band.

We finally discuss the phase noise of the ILO chain to show that it has a great potential to realize low phase-noise millimeter-wave synthesizers. Under small locking gain, the phase-noise degradation rate against subharmonic factor is not generally held to the ideal 6 dB/octave, i.e., a crossover point between the oscillator intrinsic noise and the reference signal noise [18] exists. However, the 5- and 20-GHz-band ILO chain can maintain the $20 \log(n)$ phase-noise degradation rate because the injection signal level is set higher than the crossover point. That is, the crossover point of the 20-GHz-band ILO as second stage is −5-dBm injection power at any subharmonic owing to the buffer amplifier, where the first stage 5-GHz-band ILO output powers of more than 7 dBm. The phase-noise characteristics of the ILO's are available even at millimeter-wave frequencies since the oscillation signal of each ILO is locked by the large level reference signal amplified by the buffer amplifier.

On the other hand, there is a serious problem in that the phase-noise degradation of injection oscillators increases with signal injection, which is away from the center of the locking range. Adding a frequency-tuning function such as a variable phase shifter to the oscillation loop is an effective solution [19]. This is because the oscillation frequencies are easily controlled at the center of locking range, providing low phase-noise sources. Furthermore, a tuning function can also adjust the center frequencies of first- and second-stage ILO's.

V. Conclusion

A subharmonic ILO–MMIC chain has been proposed for simple and cost-effective millimeter-wave sources. 5- and 20-GHz-band ILO MMIC's were fabricated and combined in a chain to achieve a pure output with low spur levels. Measurement results show that the ILO chain is extremely suitable for realizing full monolithic, low-cost, and low phase-noise millimeter-wave synthesizers without using expensive RF filters at the output port. Furthermore, the ILO–MMIC chain configuration is easily applicable to other frequencies with some modification in the loop design, resulting in the rapid design of millimeter-wave systems and a great reduction in MMIC development cost.

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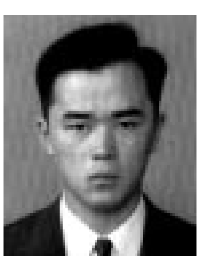

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