A Millimeter-Wave Band MMIC Dual-Quadrature Up-Converter Using Multilayer Directional Couplers

Akira Minakawa, *Member, IEEE,* Toshikazu Imaoka, *Member, IEEE,* and Nobuaki Imai, *Member, IEEE*

***Abstract*—This paper describes a newly developed monolithic-microwave integrated circuit (MMIC) dual-quadrature up-converter with very high local oscillator (LO) signal leakage suppression and good LO and RF return loss for use in the millimeter-wave band. The dual-quadrature LO suppression technique is also described, and the requirements for an imbalance in the quadrature couplers to obtain large LO suppression are clarified. The up-converter consists of two unit mixers and two high-performance multilayer directional couplers. These high-performance directional couplers enable large LO suppression. In an LO frequency range from 42.5 to 47.5 GHz, the MMIC up-converter achieved a conversion loss of less than 17±1 dB, and the LO was suppressed 22±4 dB lower than the desired RF output signal, which is the greatest value among those reported.**

I. Introduction

The SMALL size and reproducible performance of monolithic-microwave integrated circuits (MMIC's) are contributing greatly to reductions in the cost and size of microwave/millimeter-wave circuits. A frequency up-converter is one of the most important circuits in microwave/millimeter-wave radio systems. In an up-converter, it is difficult to reject a local oscillator (LO) signal using a filter because the LO and desired radio-frequency (RF) signals are close in frequency. In order to provide good LO signal leakage suppression without using filters at the RF output port, up-converters often employ a balanced-type configuration. In addition, since filters are difficult to implement on an MMIC chip due to the MMIC's low Q property, a balanced-type configuration is extremely practical in MMIC's.

A few reports about millimeter-wave band MMIC up-converters have been published [1], [2]. Hirota *et al.* [1] have reported an MMIC balanced up-converter with a 50–62-GHz operating frequency range. This up-converter has a very small chip size, but maximum LO leakage suppression is 12 dB. Wang *et al*. [2] have reported a diode-balanced up-converter with a 56–64-GHz operating frequency range, but they do not mention LO leakage suppression.

In this paper, we describe a newly developed millimeter-wave band MMIC dual-quadrature up-converter with a balanced-type configuration. A dual-quadrature type has the advantage of good LO and RF return loss characteristics. The up-converter employs new multilayer directional couplers [3], which were developed in our laboratories as high-performance 3-dB quadrature divider/combiner circuits. A multilayer MMIC technique [4], [5] is also employed to improve the design flexibility. The requirements for an imbalance in the quadrature couplers to obtain large LO suppression are clarified. Based on this design, an LO leakage suppression of 22±4 dB lower than the desired RF output signal could be achieved, and good LO and RF return loss in the millimeter-wave band could also be achieved.

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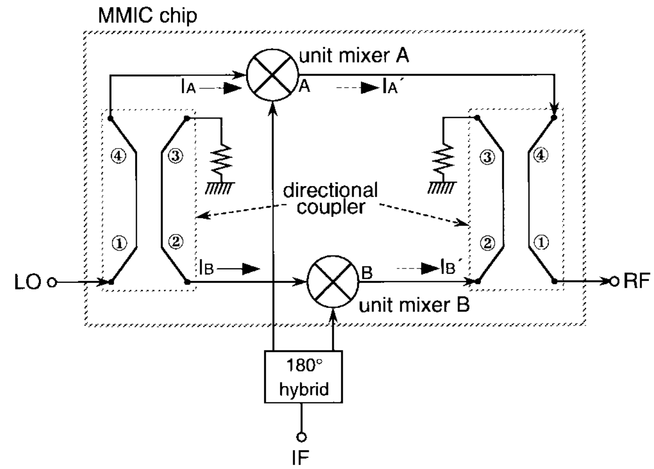


Fig. 1. Block diagram of the MMIC dual-quadrature up-converter.

II. MMIC Dual-Quadrature Up-Converter Design

A. Circuit Configuration

A block diagram of the MMIC dual-quadrature up-converter is shown in Fig. 1. It consists of two identical unit mixers, which are single-ended up-converters, and two newly developed multilayer directional couplers, which are 3-dB quadrature divider/combiner circuits. The IF input signal is split into out-of-phase signals using a 180° hybrid that is externally connected. The dual usage of the 3-dB quadrature coupler provides two important characteristics: good LO to RF isolation without filters and good LO and RF return loss.

Here we explain how the 3-dB quadrature coupler provides good LO return loss. This approach is similar to that used with balanced amplifiers using 3-dB quadrature couplers. Since the two unit mixers are identical, reflection coefficients of the unit mixers are equal and reflected signals from unit

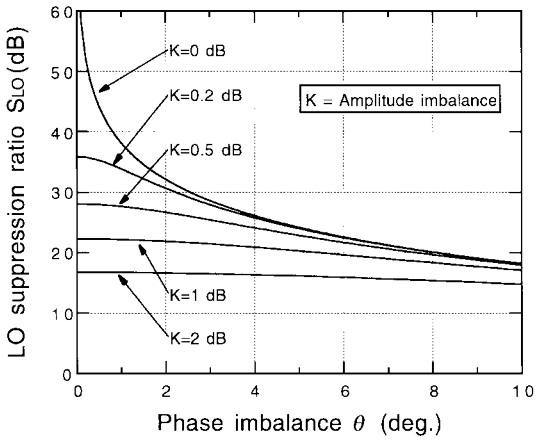


Fig. 2. LO suppression ratio versus phase and amplitude imbalance.

mixers A and B retain their quadrature and equal amplitude relationship. Because the reflected signal from unit mixer A is shifted an additional 90°, the two reflected signals from unit mixers A and B are canceled at the LO input port and the dual-quadrature up-converter has a good LO input return loss. Likewise, the dual-quadrature up-converter has good RF return loss.

B. Up-Converting Process

As shown in Fig. 1, the LO signal is fed to the unit mixer through an LO directional coupler, and the IF signal is fed through an external 180° hybrid. This provides a 90° phase difference between the LO and IF signals applied to the unit mixers. The two up-converted RF signals and the two LO leakage signals I'_{A} and I'_{B} appear at the outputs of the mixers. The RF signal at point B is +90° relative to point A, and the LO leakage signal I'_{B} at point B is −90° relative to point A. These signals are combined in an RF directional coupler. As a result, the LO leakage signals are canceled, and only the RF output signal remains.

C. LO Leakage Suppression

As mentioned above, under ideal conditions (perfect quadrature couplers and identical unit up-converters), LO leakage signals are completely canceled. However, the LO leakage signals are not completely canceled because the quadrature couplers and unit mixers used in a practical up-converter have both phase and amplitude imbalance. In this section, we will give the relationship between LO leakage suppression and amplitude/phase imbalance.

Unit mixers A and B have LO leakage currents I'_{A} and I'_{B} respectively (see Fig. 1). I'_{A} and I'_{B} are combined at the RF quadrature coupler. If the phase difference of the quadrature couplers deviates from 90°, or if the output current I'_{A} is not equal to I'_{B}, LO leakage current I_{leak} appears at the RF output port. I_{leak} is expressed as

$$I_{\mathrm{leak}} = \sqrt{I'^2_{\mathrm{A}} + I'^2_{\mathrm{B}} - 2 \cdot I'_{\mathrm{A}} \cdot I'_{\mathrm{B}} \cdot \cos\theta} \qquad (1)$$

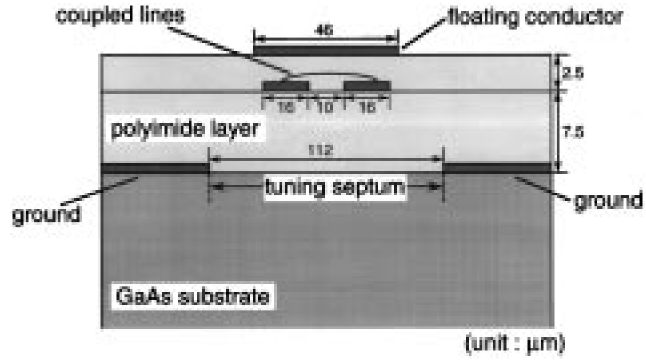


Fig. 3. Cross-sectional view of the multilayer directional coupler used for the up-converter.

where θ is the total phase imbalance. When the total amplitude imbalance is K dB, (1) is given by

$$I_{\mathrm{leak}} = \sqrt{I'^2_{\mathrm{A}} + \left(10^{-\frac{K}{20}} \cdot I'_{\mathrm{A}}\right)^2 - 2 \cdot I'_{\mathrm{A}} \cdot 10^{-\frac{K}{20}} \cdot I'_{\mathrm{A}} \cdot \cos\theta} \qquad (2)$$

where

$$K = \left| 20 \log \frac{I'_{\mathrm{B}}}{I'_{\mathrm{A}}} \right|.$$

The LO suppression ratio S_{LO} is defined as the ratio of I_{leak} to LO input current I_{IN}. Therefore, S_{LO} is given by

$$S_{\mathrm{LO}}(dB) = -20 \log \frac{I_{\mathrm{leak}}}{I_{\mathrm{IN}}}. \qquad (3)$$

Given that LO input current $I_{\mathrm{A}} + I_{\mathrm{B}}$ is equal to $\sqrt{2} I'_{\mathrm{A}}$, from (3) we can obtain

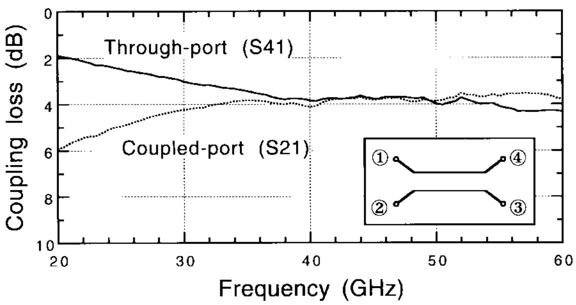
$$\begin{aligned} S_{\mathrm{LO}}(dB) &= -20 \log \frac{\sqrt{I'^2_{\mathrm{A}} + \left(10^{-\frac{K}{20}} \cdot I'_{\mathrm{A}}\right)^2 - 2 \cdot I'_{\mathrm{A}} \cdot 10^{-\frac{K}{20}} \cdot I'_{\mathrm{A}} \cdot \cos\theta}}{\sqrt{2} I'_{\mathrm{A}}} \\ &= -10 \log \frac{1 + 10^{-\frac{K}{10}} - 2 \cdot 10^{-\frac{K}{20}} \cdot \cos\theta}{2}. \end{aligned} \qquad (4)$$

The behavior of LO suppression ratio versus amplitude and phase imbalance is shown in Fig. 2. Assuming that the performance of the unit mixers on an MMIC chip is equal, amplitude and phase imbalance is dominated by the quadrature couplers. For example, when $K = 0$ dB, in order to achieve an LO suppression ratio over 40 dB, a phase imbalance of less than 0.8° is required within a particular frequency range.

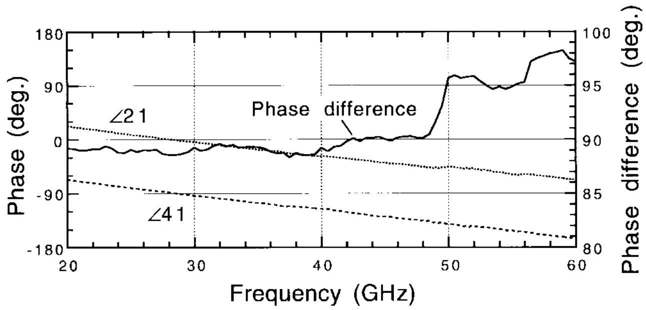
III. MMIC Dual-Quadrature Up-Converter Elements

A. Multilayer Directional Coupler

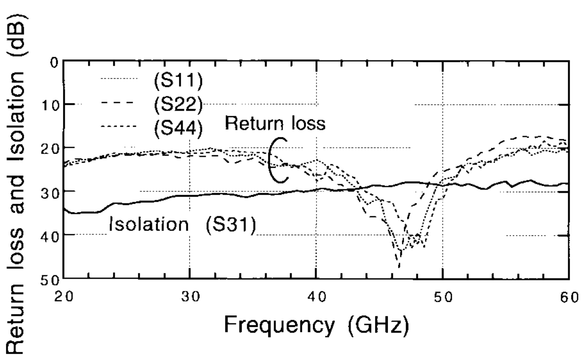
Our up-converter employs multilayer directional couplers [3] with a multilayer MMIC technique for high-performance 3-dB quadrature couplers. A cross-sectional view of the multilayer directional coupler is shown in Fig. 3. This coupler is applied as the divider/combiner circuit of the dual-quadrature up-converter shown in Fig. 1. The multilayer structure consists of four 2.5-μm-thick polyimide films ($\epsilon_{\mathrm{r}} = 3.7$) for dielectric layers fabricated on a GaAs substrate and 1-μm-thick gold



(a)



(b)



(c)

Fig. 4. Measured performance of the multilayer directional coupler: (a) coupling loss; (b) phase and phase differential; and (c) return loss and isolation.

films for the conductor metals. The thickness of the GaAs substrate is 450 μm. The directional coupler is constructed with coupled microstrip lines, a ground conductor with a tuning septum, and a floating conductor located over the coupled microstrip lines. The coupled microstrip lines are 720 μm in length. Each conductor is formed on its own dielectric layer of polyimide film. This structure makes it possible to realize the high even-mode to odd-mode impedance ratio required to achieve coupling on the order of 3 dB. By adding a floating conductor, the odd-mode impedance of the microstrip lines can be decreased; by using a septum structure, the even-mode impedance of the microstrip lines can be increased.

The measured performance of the directional coupler used in the dual-quadrature up-converter is shown in Fig. 4. The coupling loss from port 1 to ports 2 and 4 was 3.7 dB, and the phase difference between output ports 2 and 4 was 90° ± 0.2° from 42 to 48 GHz. Isolation was greater than 28 dB, and return losses were greater than 23 dB from 42 to 48 GHz. As the figure shows, since this directional coupler has perfect amplitude balance, a low-coupling loss, and accurate quadrature phase difference, it is well suited for use in the dual-quadrature up-converter.

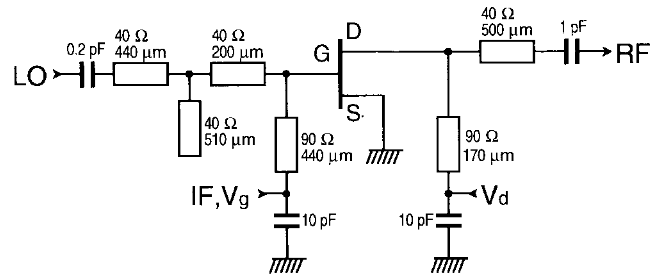


Fig. 5. Equivalent circuit of the unit mixer used for the up-converter.

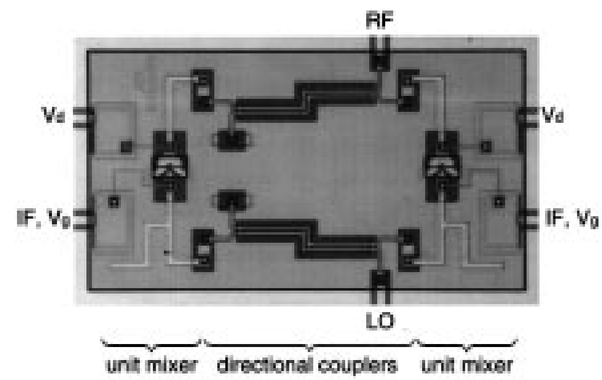


Fig. 6. A photograph of the fabricated MMIC dual-quadrature up-converter.

B. Unit Mixer

The equivalent circuit of the unit mixers is shown in Fig. 5. As shown in this figure, a gate mixer configuration [6] is employed in the unit mixers; the intermediate frequency (IF) and local oscillator (LO) signals are applied to the field-effect transistor (FET) gate and the RF signal is taken from the drain. The impedance matching networks consist of thin-film microstrip lines [5] and metal–insulator–metal (MIM) capacitors, which block a dc. The IF input signal and the gate voltage are fed through an open stub for LO port impedance matching. The active device uses a heterojunction FET [7] with a 100-μm gate width and a 0.2-μm gate length. The device has an $F_{\rm t}$ and $F_{\max}$ of 80 and 130 GHz, respectively.

IV. Performance of the MMIC Dual-Quadrature Up-Converter

A photograph of the fabricated MMIC dual-quadrature up-converter is shown in Fig. 6. The up-converter elements described above are integrated on a single chip, whose size is 1.28 mm × 2.34 mm.

On-wafer probes were used to evaluate the performance of the MMIC up-converter. Using a commercially available IF 180° hybrid, the performance of the up-converter was measured with a 6-dBm LO input. The IF frequency was set at 1 GHz. The FET drain bias was 3 V, and the drain current was 20 mA.

The measured RF output power and simulated and measured LO leakage of the up-converter as a function of LO frequency

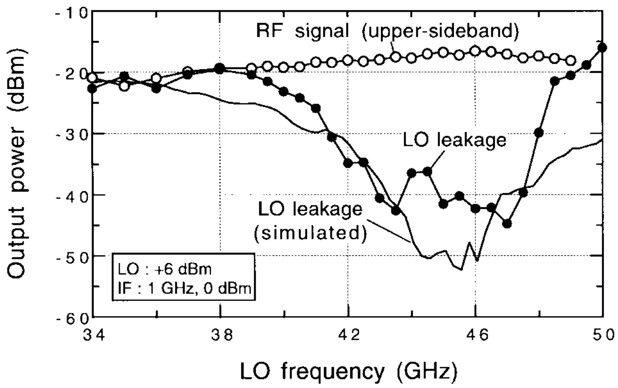


Fig. 7. Measured RF output power and simulated and measured LO leakage of the up-converter as a function of LO frequency.

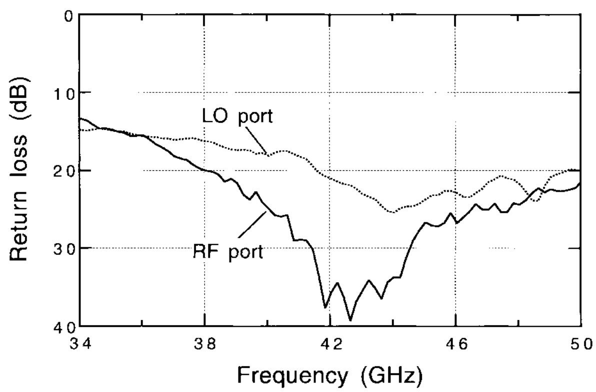


Fig. 8. Measured return loss at RF and LO ports of the up-converter.

are shown in Fig. 7. LO leakage was linearly simulated with Libra (HP-EEsof Inc.) using ideal coupler and unit mixer performance. For upper-sideband frequencies, conversion loss was less than 17 ± 1 dB for LO frequencies from 42.5–47.5 GHz. LO leakage power suppression was 22$\pm$4 dB lower than the up-converted upper-sideband signal, and it was confirmed that the simulated LO leakage value agreed with the measured value. The up-converter achieved an LO leakage suppression of over 40 dB compared to LO input power (+6 dBm). The high LO leakage suppression was achieved by the good amplitude balance and accurate 90° phase difference of the multilayer directional couplers. Since the two unit mixers were considered to have identical performance, this LO leakage suppression agreed well with the values obtained from (4) and in Fig. 2. On the other hand, the measured IF to RF port isolation was over 30 dB. In the up-converter, filtering the IF leakage signal at the RF port is easy because the IF frequency is low and very far from the RF frequency.

The measured return losses at the RF and LO ports are shown in Fig. 8. RF return loss is greater than 20 dB over 38 GHz, and LO return loss is also greater than 20 dB over 41 GHz. As shown in this figure, the dual-quadrature up-converter has good RF and LO return loss.

Fig. 9 shows the measured RF output power of upper-sideband frequencies as a function of IF input power at an LO frequency of 47.5 GHz. The up-converter has an output 1-dB compression point of −7.5 dBm and a saturated RF output power of −5 dBm for upper-sideband frequencies.

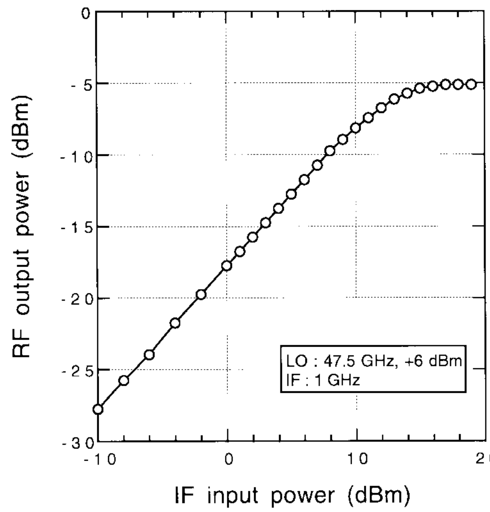


Fig. 9. Measured upper-sideband output power of the up-converter.

V. Conclusion

A millimeter-wave band MMIC dual-quadrature up-converter with good LO suppression has been developed. The up-converter consists of two unit mixers and two high-performance multilayer directional couplers. These high-performance directional couplers enable large LO suppression. In an LO frequency range from 42.5 to 47.5 GHz, the MMIC up-converter achieved a conversion loss of less than 17$\pm$1 dB, and LO was suppressed 22$\pm$4 dB lower than the desired RF output signal, which is the greatest value among those reported. The developed up-converter will be applied to millimeter-wave communication systems in the near future.

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