Wide-Band SSB Subharmonically Pumped Mixer MMIC

Hiroshi Okazaki, *Associate Member, IEEE,* and Yo Yamaguchi, *Member, IEEE*

***Abstract*— To achieve low conversion-loss and high image-rejection performance in the wide band for up and down conversion, an SSB subharmonically pumped mixer using an inphase RF divider/combiner is proposed. The SSB mixer monolithic microwave integrated circuit (MMIC) is integrated in a small area of 1.8 $\times$ 1.3 mm^2 and shows good performance at 21.6 to 30.8 GHz.**

***Index Terms*— Image-rejection mixer, monolithic microwave integrated circuit (MMIC), quasi-lumped stub, subharmonically pumped mixer, wide-band mixer.**

I. Introduction

FOR FUTURE personal radio communication systems using higher frequency bands, low-power-consumption and high-cost-performance RF equipment or circuits are desired. A subharmonically pumped mixer (SHP mixer) using an antiparallel pair of diodes is a most likely candidate for mixers because it can reduce the number of multiplier-stages, requires no dc power, and can be used for both up and down conversion [1], [2]. Furthermore, an SHP mixer with a well-matched diode pair does not output any even harmonics. In practical use, single-sideband mixers (SSB mixers) are desired. To achieve low conversion-loss and high image-rejection performance in an SSB mixer, its dividers/combiners have to be extremely accurate in amplitude and phase. A conventional type of SSB mixer for both up and down conversion needs an LO inphase divider and two quadrature hybrids at IF and RF ports [3]. Usually, IF is set at a lower frequency than RF and LO, so the IF hybrid is often excluded from an SSB mixer monolithic microwave integrated circuit (MMIC) because it requires a huge area. The RF hybrid also occupies a large area since it is in proportion to a quarter of the wave length of RF. Therefore, some approaches have been proposed to reduce the hybrid's size [4], [5], but these approaches require the sacrifice of bandwidth.

In this paper, to achieve high performance in the wide band, an SSB SHP mixer MMIC that employs a lumped Wilkinson divider, instead of a hybrid, as an RF divider/combiner is proposed. The mixer MMIC also employs the quasi-lumped technique to drastically reduce its size. The novel mixer MMIC works well for a wide bandwidth.

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II. Configuration of the Wide-Band SSB SHP Mixer

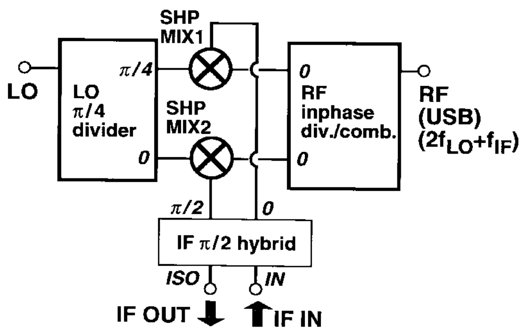
Conventional SSB mixers for both up and down conversion use an RF quadrature hybrid as an RF divider/combiner. In MMIC's, a branch-line hybrid is generally employed because it is suitable for reducing the size [5]. However, the branch-line hybrid only works in the narrow band, especially when reduced in size. On the other hand, a Wilkinson divider outputs well-balanced signals in both amplitude and phase and has lower insertion-loss, for the wide bandwidth, than branched-line hybrids, even though its lumped elements reduce the size. Therefore, to give the SSB mixer high performance in the wide RF band, the Wilkinson divider is chosen as its RF divider/combiner.

The proposed SSB mixer also has a potential to keep such performance high in the wide IF band, as mentioned below.

The image-rejection ratio is described as a function of overall amplitude and phase imbalance [3]. When these imbalances are increased, the image-rejection performance is decreased. In MMIC's, well-matched unit mixers can be obtained, so imbalances caused by the differences between mixers are negligible. Therefore, if the balances between two IF signals are completed and the frequency response of the unit mixer is flat, the imbalances are only caused by both RF and LO divider/combiner. Because a Wilkinson divider outputs well-balanced signals for the wide bandwidth, the imbalances in the conventional SSB mixer, which use a Wilkinson divider as an LO divider, are from an RF branch-line hybrid, and the imbalances in the proposed SSB mixers are from an LO divider.

The frequencies of both the desired signal and the image are changed with IF frequency, and the difference between desired and image frequencies is twice the IF. Therefore, the response of the branch-line hybrid at one of two frequencies is different from that at the other, so amplitude and phase imbalances are changed with IF frequency. To minimize the insertion-loss, an RF divider/combiner is generally designed to set its center of frequency to the desired signal. With this condition, if the IF frequency is higher, imbalances at the branch-line hybrid are larger. Thus, performance of the conventional SSB mixer is effected by IF frequency, and generally decreases at a higher IF. On the other hand, for the proposed SSB mixer, imbalances at an LO divider are not affected by the frequency of IF. So, for a given LO frequency, the proposed SSB mixer's good performance is maintained for a wide IF.

Fig. 1 shows the configuration of the wide-band SSB SHP mixer. It consists of two SHP mixers, an LO power divider with a phase shift of $\pi/4$ radians, and an RF inphase power



Up Conv.

	IF	2LO	RF-comb.	USB	LSB
MIX1	0	π/2	0	π/2	π/2
MIX2	π/2	0	0	π/2	-π/2

Down Conv.

	RF	2LO	IF-HYB	USB	LSB
MIX1	0	π/2	π/2	0	π
MIX2	0	0	0	0	0

Fig. 1. Configuration of the wide-band SSB SHP mixer.

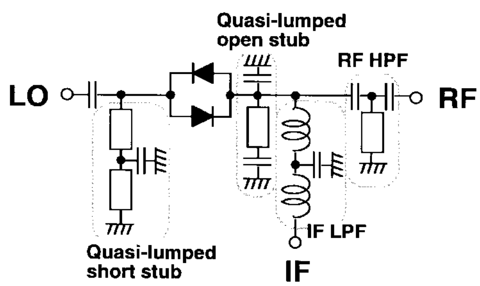


Fig. 2. Circuit diagram of the SHP mixer.

divider/combiner. These are connected to each other as shown in the figure. In this figure, upper sideband (USB) is chosen as desired signal.

For up-conversion, IF signals with frequency $f_{\rm IF}$ are input to the IF hybrid, then they are divided and fed, $\pi/2$ radians out of phase, into each mixer. LO power with frequency $f_{\rm LO}$ is divided into two signals $\pi/4$ radians out of phase. Then, SHP mixers generate the up-converted signals, and the frequencies of their major components are described as $(2f_{\rm LO} \pm f_{\rm IF})$. Between the RF ports of the mixers, up-converted USB signals $(2f_{\rm LO} + f_{\rm IF})$ are in-phase with each other and LSB components $(2f_{\rm LO} - f_{\rm IF})$ are out of phase, as shown in Fig. 1. The Wilkinson combiner combines all components in phase. Therefore, the desired up-converted USB signal appears at the output while the LSB signal is canceled.

For down-conversion, it also works as an image-rejection mixer similar to the case for up-conversion. But, as shown in Fig. 1, the down-converted USB component appears at the opposite port of the IF hybrid. Therefore, the IF input port and output port can be connected directly with a modulator and a demodulator, respectively. Thus, the IF switch, which is conventionally used to change between transmission and receiving, can be left out.

III. MMIC Design

Fig. 2 shows the circuit diagram of the SHP mixer incorporating the SSB mixer MMIC. The mixer has an IF low-pass

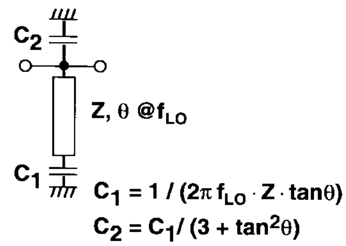


Fig. 3. Quasi-lumped $\lambda_{\rm LO}/4$ open stub.

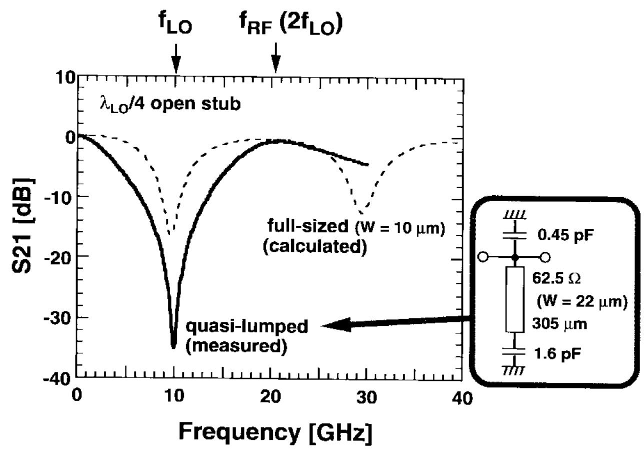


Fig. 4. Frequency response of quasi-lumped $\lambda_{\rm LO}/4$ open stub.

filter and an RF high-pass filter to isolate RF and IF ports. To isolate the RF port from the LO port, the SHP mixer generally includes two stubs: $\lambda_{\rm LO}/4$ open stub and $\lambda_{\rm LO}/4$ short stub. From the antiparallel pair of diodes, the open stub is located toward the RF port and the short stub is located toward the LO port. However, the $\lambda_{\rm LO}/4$ transmission line is very long and occupies a large area in an MMIC. To make the stubs compact, each stub is shortened by the quasi-lumped method with shunt capacitors.

The $\lambda_{\rm LO}/4$ open stub, which is simultaneously "short" at $f_{\rm LO}$, and "open" at $f_{\rm RF}\, (= 2f_{\rm LO} + f_{\rm IF} \approx 2f_{\rm LO})$, is shortened with asymmetric shunt capacitors at its ends, as shown in Fig. 3. The capacitances, C_1 and C_2, of the quasi-lumped open stub are determined as follows:

$$C_1 = \frac{1}{2\pi f_{\rm LO} \cdot Z \cdot \tan\theta}$$
$$C_2 = \frac{C_1}{3 + \tan^2\theta} \tag{1}$$

where Z is line impedance and $\theta\,(0 < \theta < \pi/2)$ is electrical length of the stub at $f_{\rm LO}$. Fig. 4 shows the measured frequency response of the open stub designed for $f_{\rm LO} = 9.7$ GHz. In the figure, W is the width of the transmission line. The calculated characteristics of the full-sized $\lambda_{\rm LO}/4$ open stub on the GaAs substrate are shown for a comparison. The suppression at $f_{\rm LO}$ of the full-sized stub is decreased by its conductor loss. The fabricated and measured quasi-lumped stubs are modified to minimize the insertion-loss at $f_{\rm RF}$ instead of $2f_{\rm LO}$, when $f_{\rm IF}$ is set to 1.0 GHz. The figure clearly shows that the quasi-lumped $\lambda_{\rm LO}/4$ open stub is compact and effectively suppresses LO leakage with low insertion loss at RF frequencies.

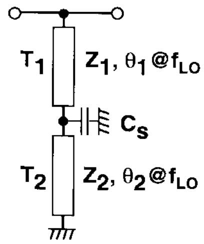


Fig. 5. Quasi-lumped $\lambda_{\rm LO}/4$ short stub.

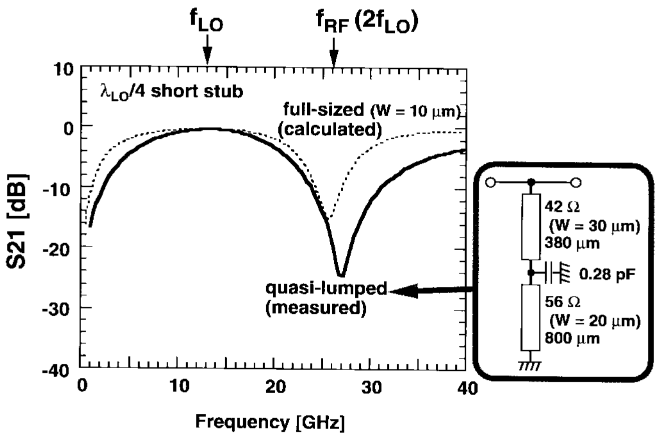


Fig. 6. Frequency response of quasi-lumped $\lambda_{\rm LO}/4$ short stub.

On the other hand, the $\lambda_{\rm LO}/4$ short stub should be simultaneously "open" at $f_{\rm LO}$, and "short" at $f_{\rm RF}\,(=2f_{\rm LO}+f_{\rm IF}\approx 2f_{\rm LO})$. And, for the SHP mixer, to effectively convert the IF signal from/to the RF, this stub should be grounded at IF frequency. As shown in Fig. 5, the quasi-lumped $\lambda_{\rm LO}/4$ short stub consists of two transmission lines, T_1 and T_2, and a shunt capacitor at the point of connection between the two lines. In the figure, Z_1 and Z_2 are line impedances, and θ_1 and θ_2 are electrical lengths of T_1 and T_2 at $f_{\rm LO}$. In aid of shorting the $\lambda_{\rm LO}/4$ stub, the limit of θ_1 and θ_2 is set to $(0<\theta_1, \theta_2<\pi/4)$. The capacitance, C_s, and θ_2 are determined as follows:

$$\tan\theta_2 = \alpha\beta - \sqrt{\alpha^2\beta^2-3}$$
$$C_s = \frac{1}{2\pi f_{\rm LO}\cdot Z_2}\left(\frac{1}{\tan\theta_2}-\beta\tan\theta_1\right)$$
$$\alpha = \left(\frac{1+3\tan^2\theta_1}{2\tan\theta_1}\right)$$
$$\beta = \frac{Z_2}{Z_1}. \qquad (2)$$

These equations are valid under the conditions described below:

$$\alpha\beta > 2$$

Fig. 6 shows the measured frequency response of the short stub designed for $f_{\rm LO}=13$ GHz. The calculated characteristics of the full-sized $\lambda_{\rm LO}/4$ short stub on the GaAs substrate are also shown in Fig. 6. In the figure, W is the width of the transmission line. The suppression at $2f_{\rm LO}$ of the full-sized stub is decreased by its conductor loss. The fabricated and measured quasi-lumped stub are modified to maximize the suppression at $f_{\rm RF}$ instead of $2f_{\rm LO}$, when $f_{\rm IF}$ is set to 1.6 GHz. The quasi-lumped $\lambda_{\rm LO}/4$ short stub is compact and effectively suppresses RF leakage with low-insertion loss at LO frequencies.

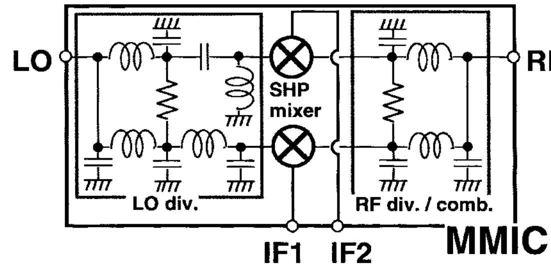


Fig. 7. Circuit diagram of the wide-band SSB SHP mixer MMIC.

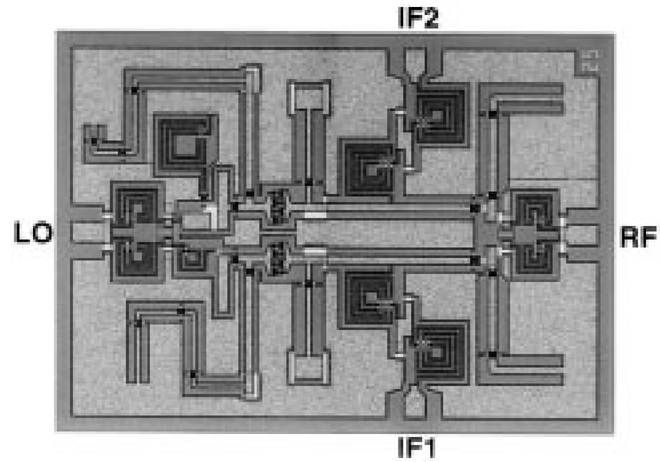


Fig. 8. Photograph of the fabricated SSB SHP mixer chip.

The circuit diagram of the SSB SHP mixer MMIC is shown in Fig. 7. The Wilkinson divider consists of lumped elements to make its size compact. The LO power divider with a phase shift of $\pi/4$ radians is realized with a lumped Wilkinson divider and L–C network. It has amplitude and phase imbalance for the wide bandwidth, though the amplitude imbalance of LO power has little effect on the performance of the SSB mixer.

IV. Experimental Results

Fig. 8 shows a photograph of the SSB SHP mixer chip fabricated with the 0.3-μm GaAs MESFET process. By using a uniplanar structure [6] and size reduction technique as described above, the K-band mixer is integrated into a small area of 1.8 mm × 1.3 mm. Each diode is realized by connecting source and drain of the FET, which has a gate width of 50 μm.

Fig. 9 shows the measured frequency response of the unit mixer for up-conversion. IF is fixed at 1.6 GHz and the input power level is −10.5 dBm. For USB, conversion gain of −12.4 ± 0.7 dB is obtained for LO frequencies from 10.0 to 15.6 GHz. The difference between USB and LSB at lower LO frequencies is mainly influenced by the RF high-pass filter. Fig. 10 shows the dependence of the conversion gain characteristics on LO input power. The frequency is fixed at 11.8 GHz for LO and 1.6 GHz for IF. Conversion gain nearly

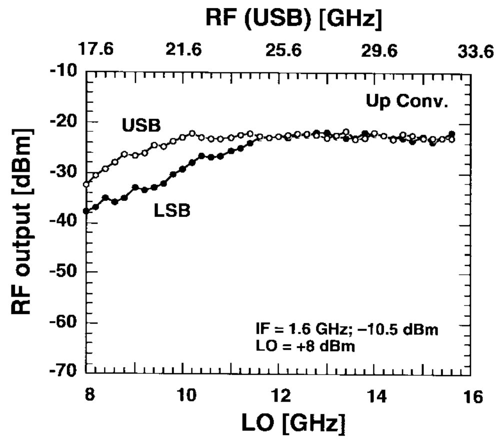


Fig. 9. Frequency response of the unit mixer, for up-conversion.

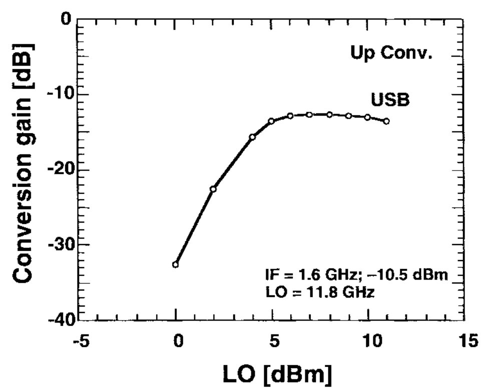


Fig. 10. Conversion gain characteristics versus LO power of the unit mixer.

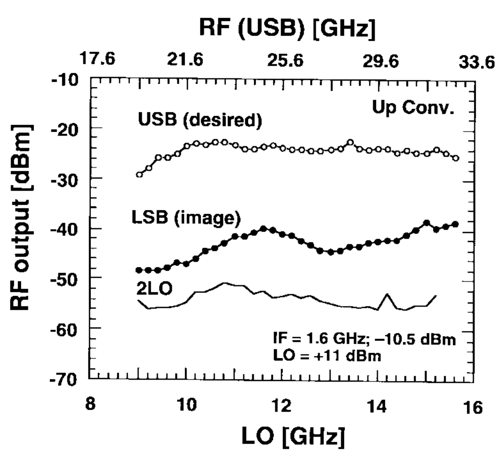


Fig. 11. Frequency response of the SSB mixer, for up-conversion.

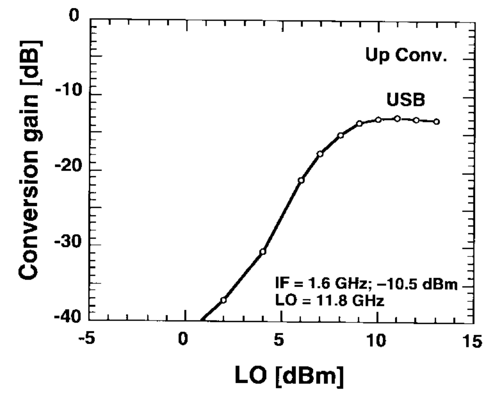


Fig. 12. Conversion gain characteristics versus LO power of the SSB mixer.

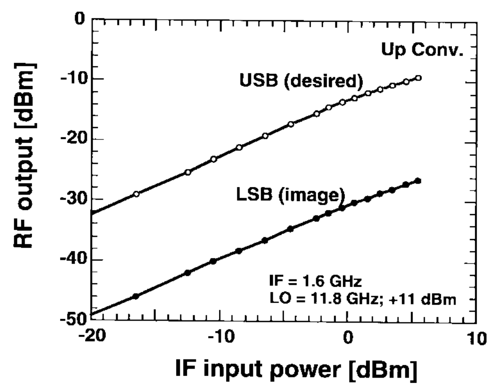


Fig. 13. RF output characteristics versus IF power of the SSB mixer.

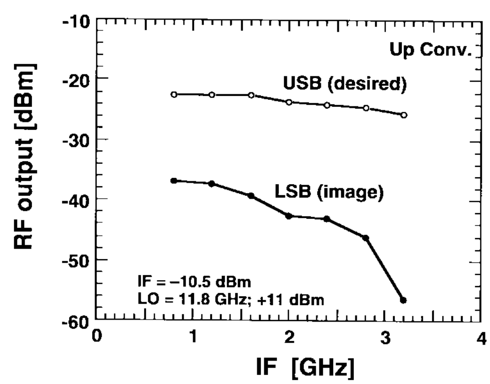


Fig. 14. IF Frequency response of the SSB mixer.

saturates for LO input power from 6 dBm to 10 dBm. It is confirmed that, at a suitable LO input power level, conversion gain is stable with slight variation in LO power. Therefore, the amplitude imbalance caused by the LO divider of the SSB mixer will be relaxed by the LO power characteristics of the unit mixer.

Measured frequency response of the proposed SSB SHP mixer for up-conversion is shown in Fig. 11. IF is fixed at 1.6 GHz and the input power level is -10.5 dBm. Conversion gain is -12.9 ± 1.1 dB and image-rejection ratio is greater than 16 dB for LO frequencies from 10.0 to 14.6 GHz. In this band, it is considered that the difference in conversion gain from the results of the unit mixer is caused by the SSB mixer configuration. The proposed SSB mixer configuration works well because the decrease of average conversion gain is estimated to be only 0.5 ($= 12.9 - 12.4$) dB. The second harmonic component of LO (2LO) is well suppressed as shown in Fig. 11.

Fig. 12 shows the dependence of the conversion gain characteristics on LO input power of the SSB mixer. The frequency is fixed at 11.8 GHz for LO and 1.6 GHz for IF. Conversion gain nearly saturates for LO input power from 10 to 13 dBm. Fig. 13 shows input/output characteristics at an LO input

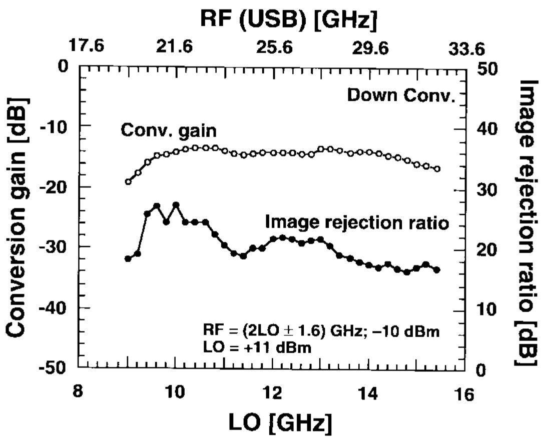


Fig. 15. Frequency response for down-conversion.

power of 11 dBm. The 1-dB compression of the conversion gain is achieved with an IF input power of 3 dBm. IF frequency characteristics with LO frequency fixed at 11.8 GHz are shown in Fig. 14. The RF outputs of desired USB signals are nearly flat, but images vary with IF frequency. The IF frequency response of the SSB mixer MMIC is expected to be flat for variable IF, so it is considered that the image variation is caused by imbalance of the IF circuit outside the MMIC.

For down-conversion, measured frequency response is shown in Fig. 15. RF input power level is set to -10 dBm. Conversion gain of -13.0 ± 1.0 dB and image-rejection ratio of better than 17 dB are obtained for the same frequency range as the up-conversion.

V. Conclusion

A compact and wide-band SSB subharmonically pumped mixer was proposed and tested. The fabricated MMIC chip is compact with a size of 1.8 mm $\times$ 1.3 mm. Measured frequency response is -12.9 ± 1.1 dB of conversion gain and better than 16 dB of image-rejection ratio for up and down conversion at RF frequencies of 21.6–30.8 GHz. This SSB mixer will be a key component in the compact transceivers for up-coming personal radio communication systems.

Acknowledgment

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References

[1] M. V. Schneider and W. W. Snell, Jr., “Harmonically pumped stlipline down-converter,” *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, pp. 271–275, 1975.
[2] M. Cohn, J. E. Degenford, and B. A. Newman, “Harmonic mixing with an antiparallel diode pair,” *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, pp. 667–673, 1975.
[3] S. A. Maas, *Microwave Mixers*, 2nd ed. Norwood, MA: Artech House, 1993, pp. 280–283.
[4] H. J. Peppiatt, J. A. Hall, and A. V. McDaniel, Jr., “A low-noise class-C oscillator using a directional coupler,” *IEEE Trans. Microwave Theory Tech.*, vol. MTT-16, pp. 748–752, 1968.
[5] T. Hirota, A. Minakawa, and M. Muraguchi, “Reduced-size branch-line and rat-race hybrids for uniplanar MMIC’s,” *IEEE Trans. Microwave Theory Tech.*, vol. 38, pp. 270–275, 1990.
[6] T. Hirota, Y. Tarusawa, and H. Ogawa, “Uniplanar MMIC hybrids—A proposed new MMIC structure,” *IEEE Trans. Microwave Theory Tech.*, vol. MTT-35, pp. 576–581, 1987.

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