INTERNATIONAL JOURNAL OF MICROWAVE AND OPTICAL TECHNOLOGY,

VOL.5, NO.6, NOVEMBER 2010

Design approach for I-Q Modulators using Millimeter-Wave Monolithic Doubly Balanced V-Band Star Mixers

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***Abstract*-In this paper, a doubly balanced V-band star mixer has been designed following the design method developed for I-Q modulators applications. The mixer has been designed using a commercial GaAs pseudomorphic HEMT process library. The mixer exhibits RF bandwidth over 45-65 GHz with local oscillator isolation better than 30 dB, and achieved a typical conversion loss of 9 dB. The IF modulation bandwidth is over 10 GHz, making the mixer suitable for high speed data transmission.**

Index Terms- **I-Q Modulator, Doubly balanced star mixer, diode mixer, monolithic microwave integrated circuit (MMIC), planar dual balun, V-band.**

I. INTRODUCTION

Recently, the 60 GHz band has gained increased academic and commercial interest mainly due to the relatively large amount of license-free and scarcely used frequency spectrum located in the proximity of 60 GHz. The exact location of these free frequency bands varies locally but the 59 – 62 GHz band overlap around the world and is therefore a true worldwide license-free band. These wide bandwidths should be compared to the much more crowded license-free ISM bands at 2.4 and 5 GHz (i.e. less than 400 MHz of overall bandwidth). The 60 GHz band has therefore been proposed as the frequency band to be used for future very high speed (several Gbps) wireless data transmission.

Within the IEEE standard body 802.15, 60 GHz is a frequency considered for Wireless Personal Area Networks (WPAN), which would allow very high data rate applications such as high-speed Internet access, streaming content download (video on demand, HDTV, home theater, etc.), real-time streaming, and wireless data bus for cable replacement.

During the last few years, a number of publications describing MMIC chip sets suitable for broadband 60 GHz applications have been published [1]. A high integration level is necessary and a single MMIC chip should contain as much of the mm-wave front-end as possible.

This paper reports on the design of 60 GHz mixer chip using a commercial foundry process based on a 0.18 μm gate length GaAs pHEMT technology intended to be used in I-Q modulators. The design phase has been preceded by a system analysis of an I-Q modulator in order to derive a design method for the related mixer and coupling structures. New design charts have been derived, allowing to define the specifications of the modulator building blocks starting from the desired modulator performance.

The paper is structured as follows: section II introduces the I-Q modulator model used and the resulting design charts, section III presents the design of the necessary star mixer, section IV outlines the simulated results for the mixer and finally, conclusions are drawn in section V.

II. I-Q MODULATOR MODEL

An analytical model of an I-Q modulator has been developed to derive design specifications of

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its building blocks: 90° coupler, mixer, Wilkinson splitter. The model has been thought to give to the designer a useful tool to determine the amplitude and phase imbalances requirements of I and Q branches starting from the SNR, EVM (or SER) and IF input power requirements. The model can be used transparently both for modulator and demodulator design.

The typical design approach is a bottom/down one: once the modulator components have been designed, its overall performance (i.e. EVM, P1dB, Image suppression, LO rejection etc.) is estimated. With this approach it's necessary to perform multiple design cycles to determine the characteristics of the components of the modulator needed to obtain the required overall specification. Within this work, the approach has been turned into a top/bottom design method, with the help of a mathematical model of the modulator and its components.

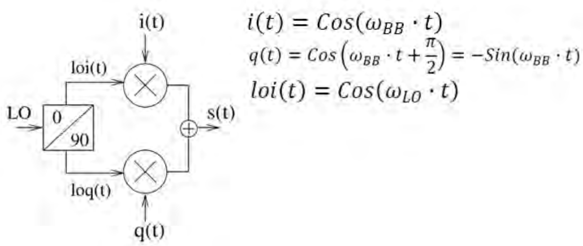

Fig.1. Proposed modulator linear model and signals expressions.

In order to derive the EVM analytical expression, a complete transmitter-receiver chain has to be introduced in the model. A linear channel (R) with additive white Gaussian noise (n), a single carrier system are introduced, supposing the I, Q transmitted components with zero mean value. The resulting model is plotted in Fig.2.

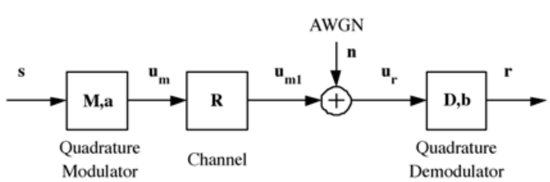

Fig.2. Transmitter, channel and receiver model used to derive EVM expression.

Solving for the expression of the demodulated signal ***r*** allows to correlate the EVM to the characteristics of the modulator. The model has been designed to correlate the amplitude (g_t) and phase (φ_t) imbalance, for a given SNR, to the EVM and the SSB (Single Side Band Suppression). A closed-form expression (see [6] for details) has been used to plot design charts which can be used by the designer to derive the required amplitude and phase imbalance from the EVM specification.

The relationship between EVM, g_t and φ_t is shown in Fig. 3. If we plot this three-dimensional graph on a plane we can get EVM contour plots as a function of g_t and φ_t. Such a plot has been drawn for a 16 QAM modulation. The resulting curves are visible in Fig.4 for a portion of the g_t and φ_t plane on which the EVM is less than 3% for an infinite SNR. In Fig. 5 the same curves are plotted for a 28 dB SNR.

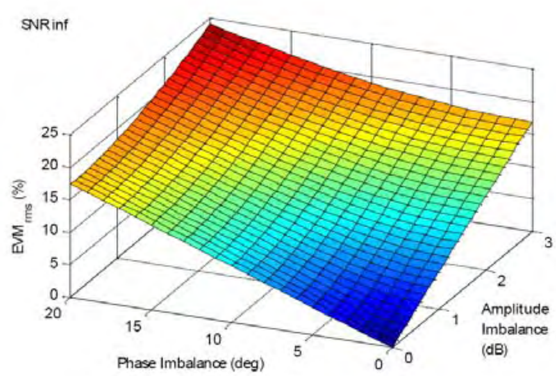

Fig.3. EVM as a function of amplitude and phase imbalance for infinite SNR

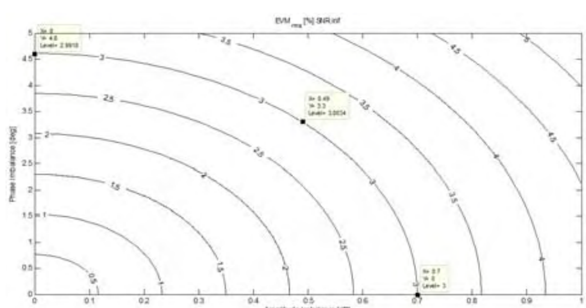

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Fig.4. EVM as a function of amplitude and phase imbalance for infinite SNR. Square points are at EVM = 3%.

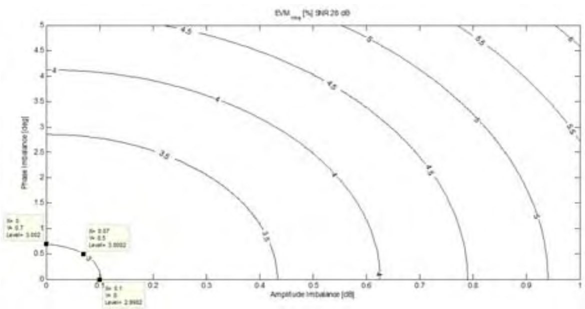

Fig.5. EVM as a function of amplitude and phase imbalance for a 28 dB SNR. Square points are at EVM = 3%.

Fig. 4 and Fig. 5 clearly demonstrate the strong dependence of the EVM on the SNR. The charts can help the designer to understand that if the SNR, estimated for the target application, is too low, the required modulator amplitude and phase balance can be too strict to be physically realized.

III. MIXER DESIGN

The analysis of the impact on the I-Q modulator EVM on the amplitude and phase imbalances naturally lead to investigate further the design of an optimum star mixer, the key nonlinear component of the modulator. The design of the mixer started from the idea to develop a very wide band modulator. The addressed RF band was 45 – 65GHz, with an IF bandwidth at least DC-3GHz. Given the above requirements, the capability of handling wide IF bandwidths and simultaneously maintaining a high LO/RF isolation is a further issue. Doubly balanced mixer (DBM) provides higher dynamic range, good port-to-port isolation, and rejection of even-order spurious responses.

Although the ring configuration is more commonly used for doubly balanced diode mixers, the star configuration exhibits an intrinsically wider IF bandwidth [2]. In recent studies, Maas and Chang successfully developed a monolithic star mixer solving the problems of traditional star mixer such as the necessity of non-planar structures [3]. Ryu modified the Maas's three coupled line balun with multi-coupled microstrip line balun and implemented the star mixer in a form that is more compatible with conventional MMICs with backside via [4]. Wideband full V-band performance using a traditional balun and novel hybrid Marchand dual balun are presented by Yeom and Ko [5] and Kim et al. [6].

Balun design started from the original structure reported in Fig. 6. Two sections of coupled lines transform the input impedance (50Ω) into the optimum diode load impedance.

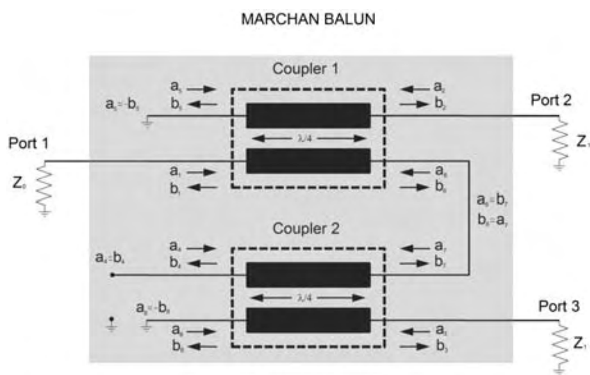

Fig.6. Marchand balun structure.

This structure has been doubled to originate the dual balun depicted in Fig. 7.

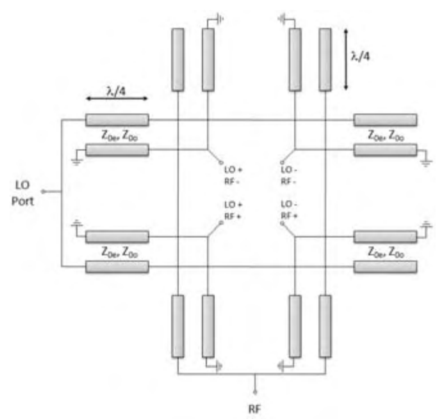

Fig.7. Designed Ideal Dual balun structure.

The structure in Fig. 7 is an ideal one since, in the MMIC layout, connection lines should be

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added to account for diode dimensions. Effects of these non idealities will be briefly discussed.

Starting from the structure in Fig. 7, the design flow has been the following:

1) Diode sizes have been selected to minimize necessary LO power.
2) Using large-signal harmonic balance simulations, the diode impedance has been computed for a given LO power.
3) Odd mode (Z_{0o}) and Even mode (Z_{0e}) impedances have been computed for the ideal dual balun in Fig. 7. Coupled lines width, length and spacing have been computed.
4) Non idealities of interconnection lines have been taken into account and a first circuit design has been performed.
5) Final EM optimization has been carried out to optimize mixer performance.

Once steps 1) to 3) have been performed, Z_{0o}=31Ω and Z_{0e}=170Ω resulted. Simulated performance of the dual balun are plotted in the following figures: results are very close to ideal ones, since an almost zero amplitude difference and near 180° phase difference are obtained.

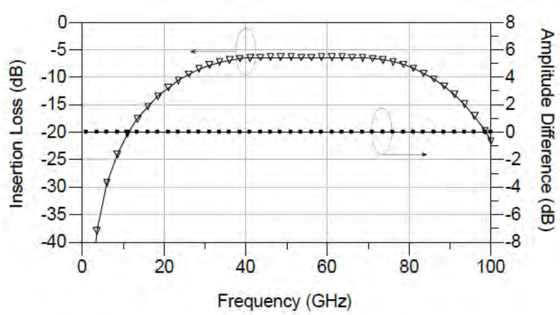

Fig.8. Ideal Dual Balun amplitude performances

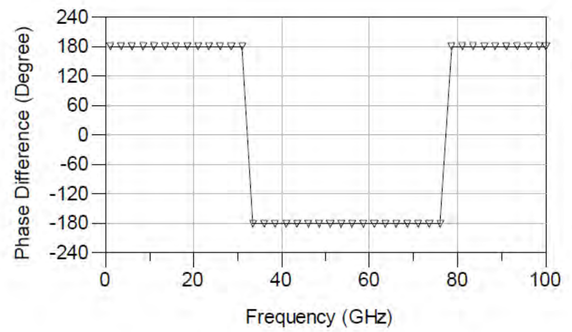

Fig.9. Ideal Dual balun phase performances

Balun performance changed significantly when the real balun structure, depicted in Fig. 10 and accounting for diodes dimensions, is taken into account.

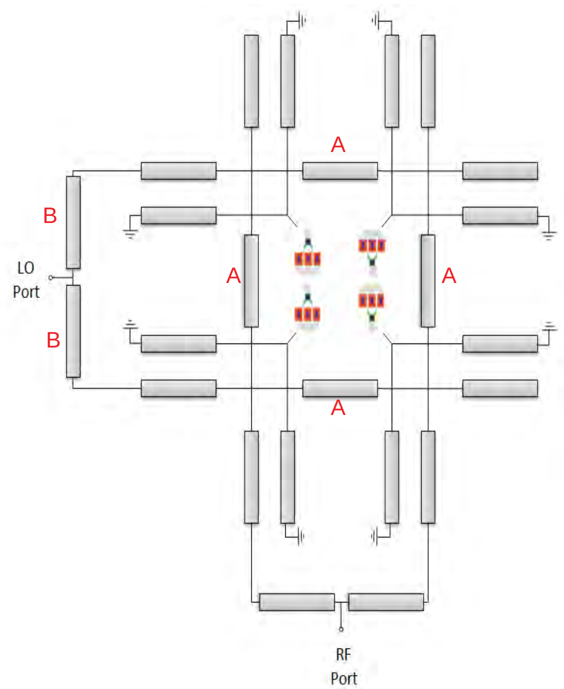

Fig.10. Real Dual Balun scheme

The most significant differences consist in the interconnection lines (*A* and *B* in Fig. 10). These lines added a 30° parasitic phase in the structure, whose effects on the balun performance are visible in Fig.11 and Fig.12.

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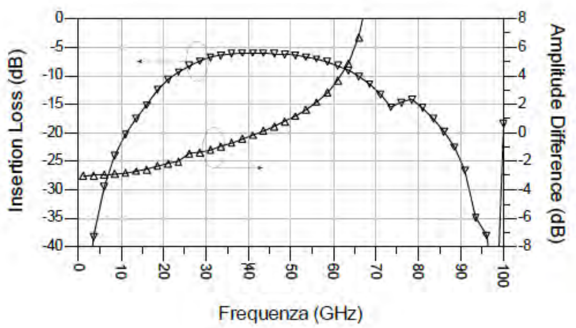

Fig.11. Effects of connection lines on the balun amplitude performance.

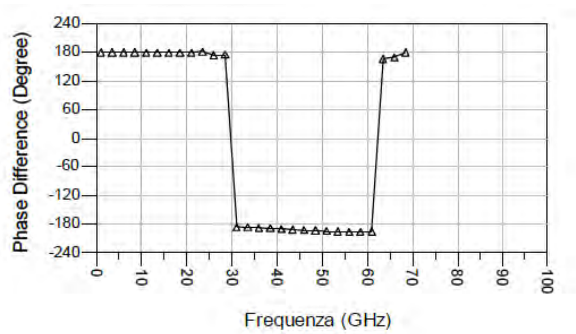

Fig.12. Effects of connection lines on the balun phase performances.

The main effect resides in a downward shift of the overall frequency response and a degradation of the ideal 180° phase difference.

To compensate the effects of these interconnection lines, beside their minimization trough an accurate layout, the balun has been optimized reducing coupled lines. Optimization was performed via electromagnetic simulations to take into account proximity of the passive structures which cannot be simulated with circuit models. In Fig. 13 and Fig. 14 are visible the final simulated performance of the balun. Fig. 15 reports differences in the phase difference between circuit and electromagnetic simulations.

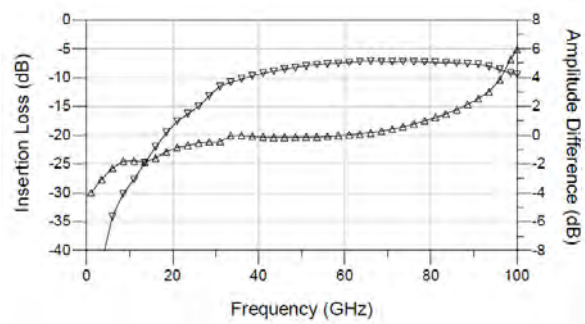

Fig.13. Optimized amplitude performances of the real balun (electromagnetic simulations).

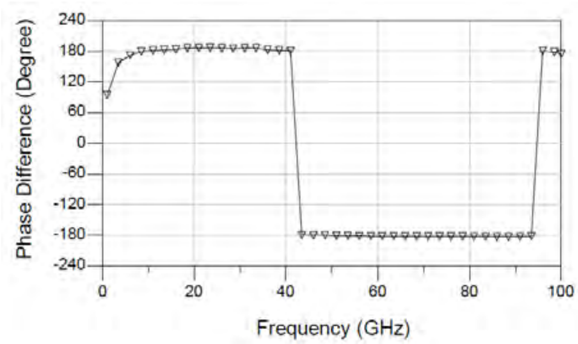

Fig.14. Optimized phase performances of the real balun (electromagnetic simulations).

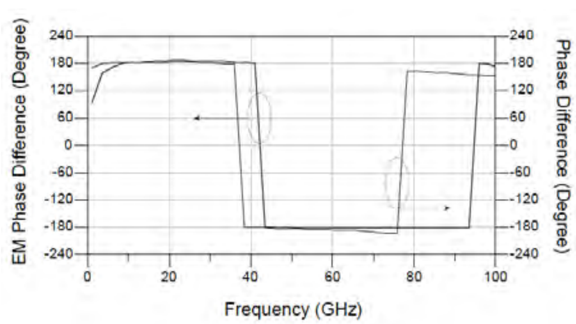

Fig.15. Phase performances of the real balun: electromagnetic vs. circuital simulations.

Simulated results of the mixer were obtained by a nonlinear circuit simulator (Agilent Advanced Design System); with -15 dBm RF power at 15 dBm LO drive, conversion gain is from -8 to -10 dB at a 100MHz fixed IF and the LO/RF isolation is better than 28 dB. RF/IF and LO/IF isolations are better than 35 dB. The RF input 1dB compression point is approximately 10dBm at 55GHz. Fig.16 shows the conversion gain at a fixed LO frequency (45GHz) tuning the RF from 45 to 65GHz: the IF 3dB band is about 12.5GHz.

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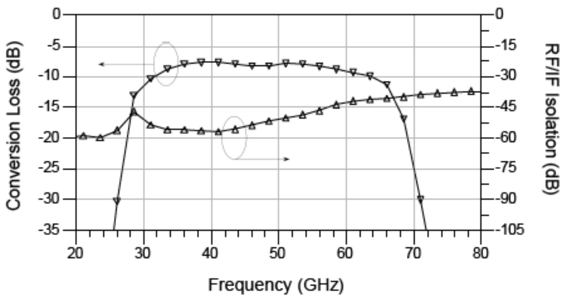

Fig.16. Mixer conversion loss and RF/IF isolation (simulated).

The mixer has been prototyped and measured up to 50GHz (higher frequency performance could not be measured, at the moment, due to instruments limitations). Fig. 17 reports the mixer insertion loss for 140MHz and 5GHz IF with a PLO of around 9dBm.

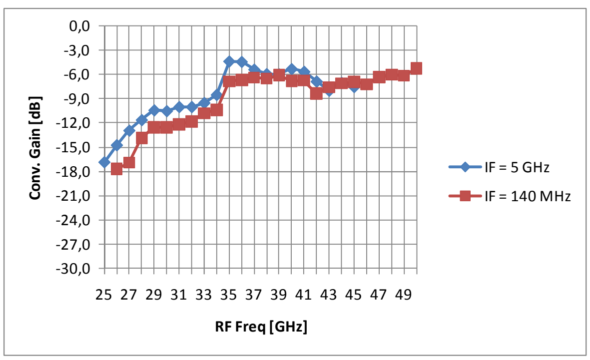

Fig.17. Mixer conversion loss and RF/IF isolation (measured).

Measured performance is aligned with the simulations except that the required PLO is much lower than the one predicted by simulations: 9dBm instead of 15dBm. The simulated LO/RF isolation is reported in Fig.18 while the measured one is in Fig. 19.

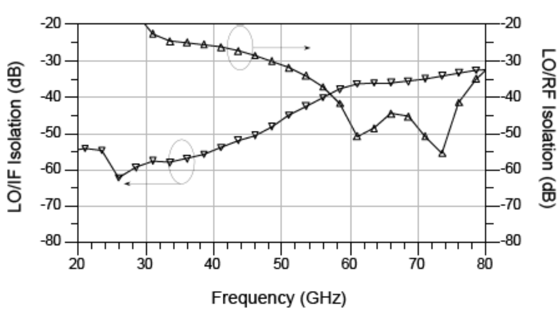

Fig.18. Mixer LO/IF isolation (simulated).

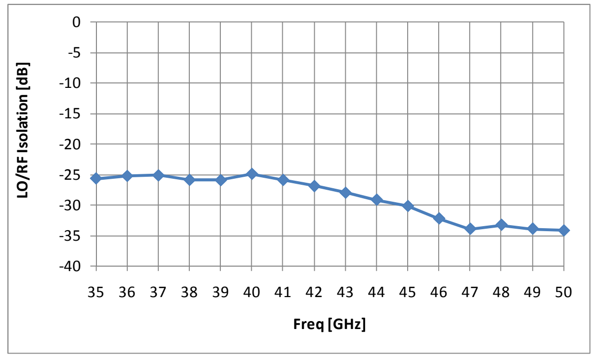

Fig.19. Mixer LO/IF isolation (measured).

Again a good agreement between simulations and measurements is obtained.

The photo of the prototyped mixer is visible in Fig. 20. The MMIC is very compact, dimensions are 1mm X 0,9mm.

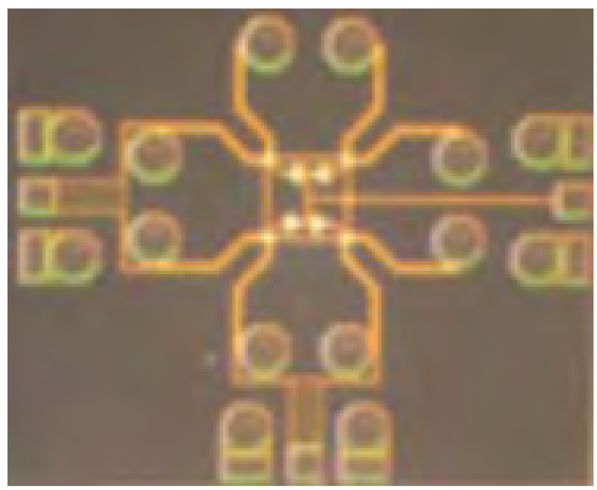

Fig.20. Realized MMIC star Mixer.

The overall mixer performance is reported in Table 1.

Table 1: Mixer performances

Parameter	Min	Typ	Max	Units
Frequency Range, RF & LO		45 - 65		GHz
Frequency Range, IF		DC - 10		GHz
PLO		9		dBm
Conversion Loss	7	9	11	dB
1dB Compression (input)		10		dBm
LO to RF Isolation	29	38	50	dB
LO to IF Isolation	37	45	52	dB
IP3 (input)		15.5		dBm

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IV. CONCLUSIONS

In this paper, an analytic approach to I-Q modulator design has been presented. Modulator design charts have been derived to facilitate building block design.

An high-performance V-band star mixer, key component for the modulator, has been designed; the required LO power is 9dBm and the size of mixer core is 1x0.9 mm^2. Furthermore, an IF modulation bandwidth of 10GHz makes the mixer suitable for high speed data transmissions (up to several Gbps). Wide IF bandwidth, up to 10GHz, makes the mixer suitable to be used with low cost 2.4GHz and 5GHz WLAN equipment to realize 60GHz WLAN transceivers.

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