A MMIC lumped element directional coupler with arbitrary characteristic impedance and its application

A. Cidronali*, G. Collodi*, M. R. Deshpande+, N. El-Zein+, H. Goronkin+, G.Manes*, V. Nair+, C. Toccafondi*

*Dept. Electronics and Telecommunications, University of Florence, V.S.Marta, 3 I-50139 Firenze - ITALY
+Physical Sciences Research Laboratory, Motorola Labs. 7700 S. River Parkway, Tempe AZ-85284 USA

Abstract - In this paper the design technique for MMIC lumped element directional couplers, based on arbitrary termination impedance, is described. Arbitrary impedance terminations allow matching the linear and nonlinear elements to the coupler without the requirement of transformer networks. The technique's capability is demonstrated through the design of a single balanced mixer prototype at 1.8GHz for which measured and simulated data are provided.

I. INTRODUCTION

The growing interest in the personal communication (PC) field has stimulated research of even more compact and integrated multifunction components. Although the PC applications span from the VHF to the millimeter-wave frequency, the most broadly diffused applications are in the low-microwave bands, the DCS-1800 MHz and the ISM band 2.45 GHz and 5.8 GHz. In order to achieve compactness and consequently a high integration of electronic functions, a monolithic implementation is highly desirable. In complex transceiver structures [1], the RF section is composed of circuits normally realized using components and sub-circuits designed by adopting a standard distributed elements approach. This is the case, for example, of amplifiers, mixers, modulators and phase shifters. These make large use of power combiners, filters, matching networks and directional couplers, which are normally designed on a distributed element basis. The monolithic implementation of such system often results in large die area, owing to the dimension of the transmission lines. Hence it is useful to consider new circuit configurations based on a lumped-element approach [2]. The implementation of the above described subsystem functions can also be approached by the use of active configurations, several examples are available in literature and in commercial solutions. They are generally very compact, and allow wide band operations. In wireless communication, may cause reduction in performance due to the increased equivalent noise temperature, a main concern is about the power consumption associated to the active solutions. Furthermore, the power handling limitation and the phase noise degradation constitute valid motivations for which completely passive solutions sustain a high interest in the MMIC applications.

This paper presents 90 degree Lumped Element Directional Couplers (LEDC) designed for a single balanced mixer application [3]. The LEDC circuit is designed considering as characteristic impedance for two out of the four ports the same value of the nonlinear elements connected to them, while the other ports maintain the 50 Ω characteristic impedance of the system. This technique allows tailoring the circuit to the specific impedance requirement of the terminating elements.

In low power circuit design zero biased nonlinear elements assume particular significance. In the case of low-level microwave signals, conventional semiconductor devices (e.g. Schottky diodes) may exhibit low nonlinear behavior, the incoming power must not be wasted by mismatch loss. In that case the circuit has to be matched to the input impedance exhibited by the terminating element at the working frequency. This is done by the use of a matching network. For that reason, a circuit design method and topologies allowing appropriate terminating impedance become relevant.

In this paper a balanced mixer based on a directional coupler and a pair of quantum functional devices (QFDs) is reported. In particular, the analytical investigation of the new circuit configuration is introduced, along with experimental results.

The implementation of a microwave circuit using QFDs is not surprising. The use of such technology for digital circuits is believed to be very close to evolve out of research into products. Thanks to QFDs' inherent features of high device functionality, high speed and low power consumption, very interesting improvements can be achieved also be shown for microwave applications, [4].

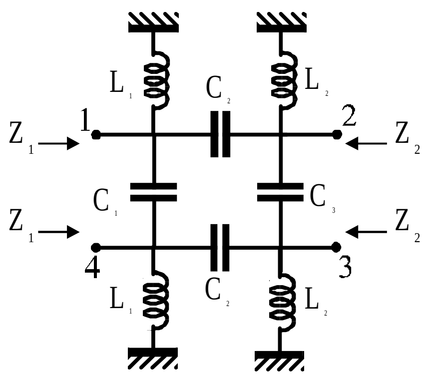

Fig.1. The proposed lumped element coupler topology

$$
Y_{LEDC} = \begin{vmatrix} \frac{1}{jw_0L_1} + jw_0C_2 + jw_0C_1 & jw_0C_2 & 0 & jw_0C_1 \\ jw_0C_2 & \frac{1}{jw_0L_2} + jw_0C_2 + jw_0C_3 & jw_0C_3 & 0 \\ 0 & jw_0C_3 & \frac{1}{jw_0L_2} + jw_0C_2 + jw_0C_3 & jw_0C_2 \\ jw_0C_1 & 0 & jw_0C_2 & \frac{1}{jw_0L_1} + jw_0C_2 + jw_0C_1 \end{vmatrix} \qquad (1)
$$

II. DESIGN TECHNIQUE

Following the general concept of implementing the directional coupling function, defined by the S-matrix, by means of lumped elements only, the first step consists of a proper guess of the circuit topology. From the analogy between the TEM directional coupler and two coupled π-LC cells, [5], it is possible to implement the electronic function for the circuit in fig.1. Relating the single components of the model to the symbolical $\underline{Y}$ matrix obtained by the scattering to admittance conversion, the value of each component is defined in closed form.

With reference to Fig.1, Z1 and Z2 are the characteristic impedances at ports 1 and 4 and at ports 2 and 3 respectively. The admittance matrix of the LEDC in symbolic form is shown in (1), where ω_0 represents the operative frequency. The scattering matrix of a directional coupler converted into the generalized admittance matrix is reported in (5) where α is the port 1 to 2 phase rotation. Comparing (1) and (5), we obtain an equation system, whose solution gives the expression of each lumped component~~s~~ in closed form. Introducing the parameters

$$
n = \frac{Z_1}{Z_2} \qquad (2)
$$

representing the ratio between the system impedance, Z_1, and the impedance associated to the termination, Z_2, and the mean value:

$$
Z = \sqrt{Z_1 \cdot Z_2} \qquad (3)
$$

The LEDC design formulae can be expressed in the following form:

$$
\begin{array}{lll} C_1 = \dfrac{\sqrt{n}}{\omega_0 \cdot Z} & C_2 = \dfrac{\sqrt{2}}{\omega_0 \cdot Z} & C_3 = \dfrac{1}{\omega_0 \cdot Z\sqrt{n}} \\ L_1 = \dfrac{Z}{\omega_0 \cdot \left(\sqrt{2} + \sqrt{n}\right)} & L_2 = \dfrac{Z}{\omega_0 \cdot \left(\sqrt{2} + \sqrt{n}\right)} & \end{array} \qquad (4)
$$

In all the relevant circuit applications ports 2 and 3 of the LEDC are terminated on circuit elements which may assume any equivalent impedance values. The matching problem between the LEDC and such terminations is solved considering the Z_2 value as a specification during the LEDC design. For practical consideration only real characteristic impedance is taken into account.

The layout is represented in Fig. 3, and is realized in coplanar technology in order to avoid the requirement for via holes. The integer design has been carried out using the Momentum tool within the HP-Agilent ADS package. This approach allows carefully dimensioning of any element and enables consideration of any E.M. coupling between different parts of the circuit, giving a further compact arrangement, [6].

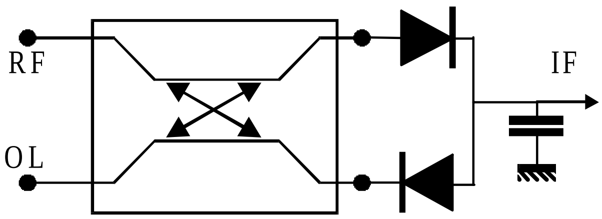

Fig. 2: schematic diagram of the single balanced mixer implemented by LEDC and tunnel diodes

In a mixer operating at microwave frequencies, at which the unbiased junction impedance becomes a dominant factor, QFDs appear to be more flexible device than the Schottky devices in this respect, [7]. Primarily, it is the fact that the barriers of a QFDs can be tailored during device designing in such a way that nonlinearities associated with the devices can be taken under control to match the microwave signal pump requirements. It is also possible in principle, to choose different layer structures for a device of the same diameter to obtain optimum resistive nonlinearities. These are the main motivations for the investigation of the single balanced mixer which schematic diagram is reported in Fig.2, where the nonlinear element are tunnel diodes biased in Vd=0V.

$$Y = \left| \begin{array}{cccc} \dfrac{1 - \exp(j4a)}{Z_1 \times (1 + \exp(j4a))} & \dfrac{- j\sqrt{2} \times (\exp(ja) + \exp(j3a))}{\sqrt{Z_1 \times Z_2} \times (1 + \exp(j4a))} & \dfrac{\sqrt{2} \times (\exp(j3a) - \exp(ja))}{\sqrt{Z_1 \times Z_2} \times (1 + \exp(j4a))} & \dfrac{2j \times \exp(j2a)}{Z_2 \times (1 + \exp(j4a))} \\ \dfrac{- j\sqrt{2} \times (\exp(ja) + \exp(j3a))}{\sqrt{Z_1 \times Z_2} \times (1 + \exp(j4a))} & \dfrac{1 - \exp(j4a)}{Z_2 \times (1 + \exp(j4a))} & \dfrac{2j \times \exp(j2a)}{Z_1 \times (1 + \exp(j4a))} & \dfrac{j\sqrt{2} \times (\exp(ja) - \exp(j3a))}{\sqrt{Z_1 \times Z_2} \times (1 + \exp(j4a))} \\ \dfrac{j\sqrt{2} \times (\exp(j3a) - \exp(ja))}{\sqrt{Z_1 \times Z_2} \times (1 + \exp(j4a))} & \dfrac{2j \times \exp(j2a)}{Z_2 \times (1 + \exp(j4a))} & \dfrac{1 - \exp(j4a)}{Z_2 \times (1 + \exp(j4a))} & \dfrac{- j\sqrt{2} \times (\exp(ja) + \exp(j3a))}{\sqrt{Z_1 \times Z_2} \times (1 + \exp(j4a))} \\ \dfrac{2j \times \exp(j2a)}{Z_1 \times (1 + \exp(j4a))} & \dfrac{\sqrt{2} \times (\exp(j3a) - \exp(ja))}{\sqrt{Z_1 \times Z_2} \times (1 + \exp(j4a))} & \dfrac{- j\sqrt{2} \times (\exp(ja) + \exp(j3a))}{\sqrt{Z_1 \times Z_2} \times (1 + \exp(j4a))} & \dfrac{1 - \exp(j4a)}{Z_1 \times (1 + \exp(j4a))} \end{array} \right| \mathbf{Di}$$

The diode at such a bias point shows an impedance value around 35Ω and a negligible reactive part. A prototype based on the LEDC and a tunnel diode pair, working at 1.8GHz has been implemented on InP substrate. The values of the LEDC circuit element have been calculated using the methodology described above, considering Z_1=50Ω and Z_2=35Ω, the latter value is imposed by the tunnel diode pair impedance at zero bias.

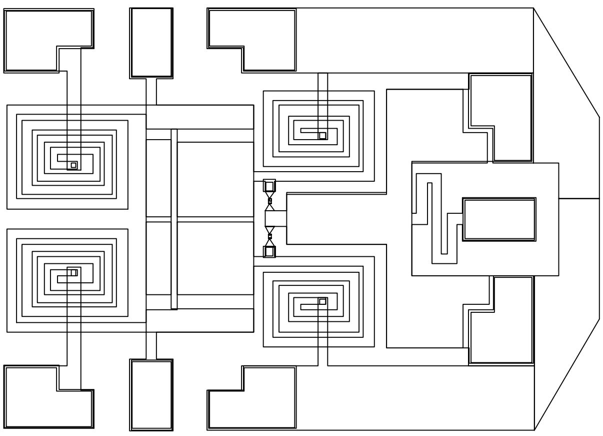

Fig. 3: layout of the single balanced mixer implemented by LEDC and tunnel diodes

The tunnel diodes used in this realization are heterojunction interband tunnel diodes (HITD's). It consists of a 500A, p+ doped InGaAs top contact layer, followed by a 500A p+ doped InAlAs layer and finally a 1000A n+ doped InGaAs bottom contact layer. These heterostructue interband tunnel diodes have shown very high current densities (50-60KA/cm^2) and peak to valley ratios between 10 and 15, [8]. Analysis of microwave performance shows a maximum frequency of oscillation around 20GHz for a 2.5x2.5μm^2.

IV. MEASUREMENTS

This section presents measurements carried out on-wafer with regard to the small signal performance of the mixer. In the LEDC part of the mixer, the value of the scattering transfer parameter for the in-phase and the in-quadrature channels are around –6dB instead of the target value of –3dB due to the parasitic components of the lumped elements. For the same reason, in the phase relationship between the two channels a deviation of 4 degrees, from the ideal value (90 degrees) has been observed.

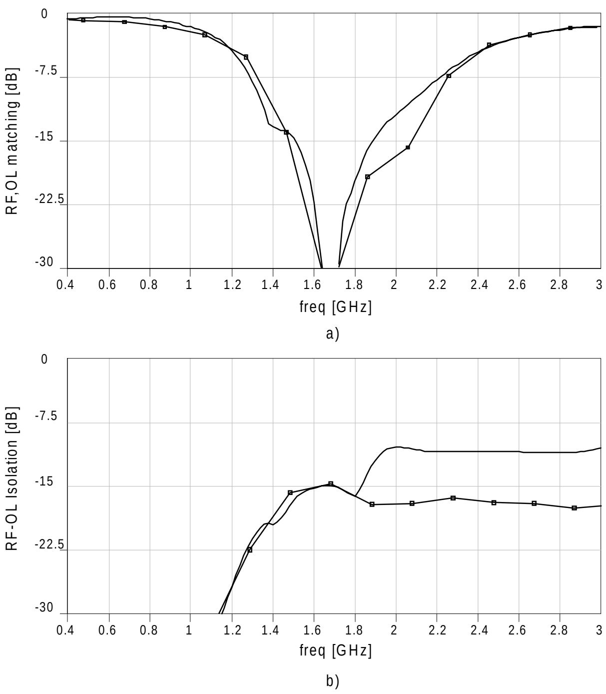

Fig. 4: Matching (a) and isolation (b) response of the LEDC- HITD based single balanced mixer prototype; symbols: measured data, lines: simulations

The small signal mixer circuit performance is presented in Figure 4, in terms of impedance matching (S11, S22) and isolation (S22) between the RF and OL port. A matching better than –25 dB and an isolation of –15dB is achieved at the center frequency. The agreement between the predicted and measured values is good in the 0.4-3 GHz band. A reasonable agreement is achieved also for the other parameters not reported here. It has been found out that, the value of unbiased junction resistance was slightly higher then the design value and the capacitance value increased of a factor 1.2. In order to validate the design technique, an update version of the diode model, characterized from the same prototype wafer has been reintroduced in the simulation schematics and the analysis re-run giving the result shown in the figures 4a and 4b. The difference between diodes feature is the main reason for the slight frequency detuning and a degradation of the performance.

Although the prototype is not optimized for the diodes, the design technique is shown to be capable of furnishing a compact solution for MMIC building block. The response regarding the nonlinear behavior of the mixer is beyond the scope of the present paper.

IV. CONCLUSION

A compact single balanced mixer for ISM application, consisting of a tunnel diode biased at 0V, has been described. The prototype working in the 1.8 GHz band has been realized on InP substrate. The results show a good isolation between the input ports and a good matching value. Work is ongoing to extend the operative frequency and to demonstrate the benefits of such a design technique in nonlinear regime of the electronic function. This work is part of a project on the applications of quantum functional devices to MMICs.

REFERENCES

[1] H. Suwaky, T. Nakagawa, T.Ohira “An MMIC local oscillator for 16-QAM digital microwave radio systems”, IEEE Tran. Microwave Theory and Tech., vol.43, no.6, June 1995 pp.1230,1235

[2] K. Ali, A. Podell “ A wide band GaAs monolithic spiral qudrature hibrid and its circuit application ” IEEE - JSSC Vol. 26 nr.10 Oct. 1991.

[3] G. Avitabile, A. Cidronali, C. Salvador, M. Speciale “A Compact MMIC 90° Coupler for ISM Applications “, IEEE - MTT-S Denver CO June 1997.

[4] A.Cidronali, G. Manes, ‘Report of a study on Quantum MMIC’ work supported by Motorola Physical Research Lab. Under contract SI-122847 Quantum MMIC Design Consulting

[5] G. Matthei, L. Young, E.M.T. Jones “ Microwave filters, impedence-matching networks and coupling structures” Artech House Books, Dedham, MA

[6] G. Avitabile, A. Cidronali, C. Salvador, “Equivalent Circuit Model of GaAs MMIC Coupled Planar Spiral Inductances”, to be appeared on International Journal on Microwave and Millimeter Wave Computer Aided Engineering, Vol.7, n°4, pp. 318-326, 1997W. Y. Liu, D.

[7] P. Steenson,’Investigation of subharmonic mixer based on a quantum barrier device’, IEEE Tran. Microwave Theory and Tech., vol.48, no.4, April 2000 pp.787-763

[8] N. El-Zein, M. Deshpande, G. Kramer, J. Lewis, V. Nair, M. Kyler, S. Allen, and H. Goronkin, ‘DC and RF Characterization of Different Heterojunction Interband Tunneling Diodes’, International Conference on Indium Phosphide and Related Materials, May 2000, pp. 146-149