A CMOS RF front-end Switch Topology

[1]Robson N. de Lima and [2]Bernard Huyart

[1]Universidade Federal da Bahia-UFBA, Salvador-BA, Brazil
[2]École Nationale Supérieure des Télécommunications-ENST, Paris-France

abstract - **This paper describes a CMOS RF Single Pole Double Through (SPDT) switch used in the front-end of a transceiver. Its topology is based on the association of an active quasi-circulator and an RF Single Pole Single Through (SPST) Switch.**

I. INTRODUCTION

In various wireless communications systems the transmission (TX) and reception (RX) of signals are not simultaneous, such as in the GSM and BLUETOOTH wireless systems. In situation where a unique antenna is used, a RF switch may alternately enable and disable the paths between TX or RX and the antenna. For cellular applications, this switch is normally realized with GaAs MESFET structures [1], providing a good isolation between the TX and RX paths.

With the advent of the ‘Radio on Chip’, the ultimate goal is the integration of a transceiver on a single CMOS-die. However, the silicon substrate losses make difficult to obtain a RF switch with a good TX/RX isolation in CMOS standard technologies.

In this work, we report a RF front-end switch topology composed of a quasi-circulator [2] and a SPST switch (figure 1) with potential applications in silicon monolithic CMOS.

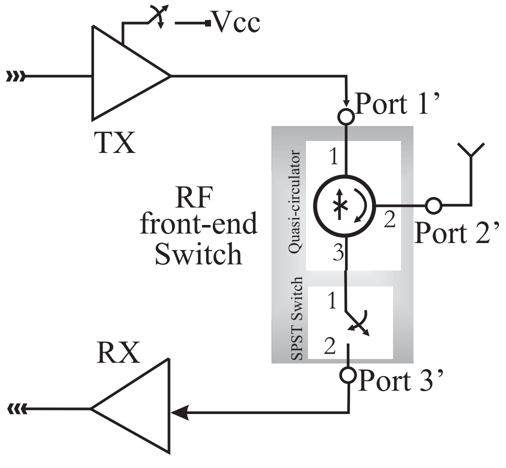

Figure 1: Block Diagram of the RF front-end Switch

The operating principle of this circuit can be described as such: during the transmission the SPST switch is opened, providing a TX/RX isolation that is function of quasi-circulator and SPST switch isolations. Taking into account that during the reception operation mode of the transceiver, the emitter is turned off [3], the SPST switch is closed. Then the RX/TX isolation is obtained by the own non-reciprocity of the quasi-circulator.

II. THEORETICAL CONSIDERATIONS

To show that the TX/RX isolation is the sum of the quasi-circulator and switch isolation, let’s consider scattering matrix of the quasi-circulator [S^{qc}] and the SPST switch [S^{sw}] where superscripts *qc* and *sw* are used on the matrix elements. Then the scattering matrix of the proposed RF front-end switch is given by (1).

$$[S] = \begin{bmatrix} S_{11}^{qc} + \dfrac{S_{13}^{qc} \cdot S_{11}^{sw} \cdot S_{31}^{qc}}{1 - S_{11}^{sw} \cdot S_{33}^{qc}} & S_{12}^{qc} + \dfrac{S_{13}^{qc} \cdot S_{11}^{sw} \cdot S_{32}^{qc}}{1 - S_{11}^{sw} \cdot S_{33}^{qc}} & \dfrac{S_{13}^{qc} \cdot S_{12}^{sw}}{1 - S_{11}^{sw} \cdot S_{33}^{qc}} \\ S_{21}^{qc} + \dfrac{S_{23}^{qc} \cdot S_{11}^{sw} \cdot S_{31}^{qc}}{1 - S_{11}^{sw} \cdot S_{33}^{qc}} & S_{22}^{qc} + \dfrac{S_{11}^{sw} S_{32}^{qc} S_{23}^{qc}}{1 - S_{11}^{sw} S_{33}^{qc}} & \dfrac{S_{12}^{sw} S_{23}^{qc}}{1 - S_{11}^{sw} S_{33}^{qc}} \\ \dfrac{S_{31}^{qc} \cdot S_{21}^{sw}}{1 - S_{11}^{sw} \cdot S_{33}^{qc}} & \dfrac{S_{32}^{qc} \cdot S_{21}^{sw}}{1 - S_{11}^{sw} \cdot S_{33}^{qc}} & \dfrac{S_{21}^{sw} \cdot \left(\dfrac{S_{12}^{sw}}{1 - S_{11}^{sw} \cdot S_{33}^{qc}} - S_{12}^{sw} \right)}{S_{11}^{sw}} + S_{22}^{sw} \end{bmatrix} \quad (1)$$

With the assumption that the port 3 of the quasi-circulator is well matched $S_{33}^{qc} \ll 1$, (1) becomes (2).

$$[S] \approx \begin{bmatrix} S_{11}^{qc} + S_{13}^{qc} \cdot S_{11}^{sw} \cdot S_{31}^{qc} & S_{12}^{qc} + S_{13}^{qc} \cdot S_{11}^{sw} \cdot S_{32}^{ci} & S_{13}^{ci} \cdot S_{12}^{sw} \\ S_{21}^{qc} + S_{23}^{qc} \cdot S_{11}^{sw} \cdot S_{31}^{qc} & S_{22}^{qc} + S_{11}^{sw} \cdot S_{32}^{qc} \cdot S_{23}^{qc} & s_{12}^{sw} \cdot s_{23}^{qc} \\ S_{31}^{qc} \cdot S_{21}^{sw} & S_{32}^{qc} \cdot S_{21}^{sw} & S_{22}^{sw} \end{bmatrix} \quad (2)$$

Using the quasi-circulator architecture of Gasmi [4], the forward and reverse transmission coefficients of the port 1 to 3 are small and the isolation value of port 3 to 2 is negligible. Then (2) becomes (3).

Robson N. de Lima is with Universidade Federal da Bahia-UFBA , EP- Departamento de Engenharia Elétrica, Grupo de Microeletrônica, Rua Aristides Novis, 2, Federação, 40210-630 Salvador-BA Brazil, Phone: +55 71 237 2367 Fax: +55 71 336 1288. Email: delima@ufba.br

Bernard Huyart is with École Nationale Supérieure des Télécommunications-ENST-Paris France; 46, rue Barrault 75634 Cedex 13 Paris; huyart@com.enst.fr

$$[S] \approx \begin{bmatrix} S_{11}^{qc} & S_{12}^{qc} + S_{13}^{qc} \cdot S_{11}^{sw} \cdot S_{32}^{qc} & S_{13}^{qc} \cdot S_{12}^{sw} \\ S_{21}^{qc} & S_{22}^{qc} + S_{11}^{sw} \cdot S_{32}^{qc} \cdot S_{23}^{qc} & S_{12}^{sw} S_{23}^{qc} \\ S_{31}^{qc} \cdot S_{21}^{sw} & S_{32}^{qc} \cdot S_{21}^{sw} & S_{22}^{sw} \end{bmatrix} \tag{3}$$

Since the proposed switch topology has a SPST switch, operating in ON-OFF states, we have two scattering matrix for the RF front-end switch, one for transmission and another one for the reception.

During the transmission mode of the transceiver, signal flow from port (1') to port (2'), the SPST Switch is kept opened. In this way, the reflection coefficients at port 1' $(S_{1'1'})_{tx}$ and port (2') $(S_{2'2'})_{tx}$ are given by (4) and (5), respectively.

$$(S_{1'1'})_{tx} = S_{11}^{qc} \tag{4}$$

$$(S_{2'2'})_{tx} = S_{22}^{qc} + (S_{11}^{sw})_{off} \cdot S_{32}^{qc} \cdot S_{23}^{qc} \tag{5}$$

where subscript *off* indicates the current state of the SPST switch.

The isolation between the transmission and reception paths $(S_{3'1'})_{tx}$, i.e., the signal flow from port (1') to port (3'), is given by (6).

$$(S_{3'1'})_{tx} = S_{31}^{qc} \cdot (S_{21}^{sw})_{off} \tag{6}$$

Expressing (6) in dB, it becomes (7).

$$[(S_{3'1'})_{tx}]_{dB} = 20\log S_{31}^{qc} + 20\log\left(S_{21}^{sw}\right)_{off} \tag{7}$$

where, $20\log S_{31}^{qc}$ represents the quasi-circulator isolation and $20\log\left(S_{21}^{sw}\right)_{off}$ the SPST switch one.

Thus, the TX/RX isolation of the RF front-end switch proposed here, can be the sum of the individual isolations of the quasi-circulator and the SPST switch.

During the reception operation mode of the transceiver, the SPST switch is closed. Under this condition, the reflection coefficients at port (2') and (3') are respectively given by (8) and (9) .

$$(S_{2'2'})_{rx} = S_{22}^{qc} + (S_{11}^{sw})_{on} \cdot S_{32}^{qc} \cdot S_{23}^{qc} \tag{8}$$

$$(S_{3'3'}) = (S_{22}^{sw})_{on} \tag{9}$$

and the transmission coefficient from port (2') to port (3') is given by (10).

$$(S_{3'2'})_{rx} = S_{32}^{qc} \cdot (S_{21}^{sw})_{on} \tag{10}$$

where subscript *on* indicates the current state of the SPST switch.

The isolation from port (3') to port (1') is given by (11).

$$[S_{1'3'}]_{rx} = S_{13}^{qc} \cdot (S_{12}^{sw})_{on} \tag{11}$$

Port (2') is connected to the antenna. Its reflection coefficient must be small and depends on both reflections coefficients of the SPST switch - corresponding to ON and OFF states. According to (5) and (8), this small value of the reflection coefficient can be achieved by doing $S_{23}^{qc} \approx 0$, for the situation in which some gain $S_{32}^{qc} > 1$ in the RX path is desired.

III. SPDT TOPOLOGY

The topology of the SPDT (figure 2) is based on the association of a SPST switch and the quasi-circulator proposed by Gasmi [4]. This last one has been realized on GaAs substrate [2,4].

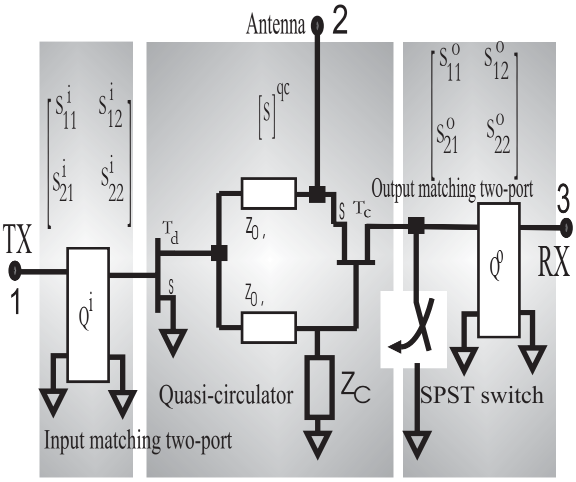

Figure 2: Schematic of the RF front-end switch

The isolation between ports is obtained by the non-reciprocity of the transistor and by connecting an in-phase divider to an out-of-phase combiner and plus by the SPST isolation. The divider is achieved by using a common source transistor T_d, a input matching two-port Q^i and a junction constituted of 90º phase shifters. The combiner consists of a transistor T_c. The SPST switch may be realized in series, shunt or series-shunt scheme. But here, it is putted in shunt scheme, such as the matching condition at port (3') is achieved easily with an output matching two-port Q^o.

Modeling the transistor by its transconductance, the scattering matrix of the SPDT front-end switch is given by (12).

$$[S] = \begin{bmatrix} S_{11}^{i} + \dfrac{S_{12}^{i} S_{21}^{i}}{1 - S_{22}^{i}} & 0 & 0 \\ \dfrac{S_{21}^{i}}{1 - S_{22}^{i}} \cdot S_{21}^{qc} & S_{22}^{qc} & 0 \\ \dfrac{S_{21}^{o} S_{21}^{i}}{\left(1 - S_{22}^{i}\right)\left(1 - S_{11}^{o}\right)} \cdot S_{31}^{qc} & \dfrac{S_{21}^{o}}{1 - S_{11}^{o}} \cdot S_{32}^{qc} & S_{22}^{o} + \dfrac{S_{12}^{o} S_{21}^{o}}{1 - S_{11}^{o}} \end{bmatrix} \quad (12)$$

where the superscripts '*i*' concerns to the parameters of the input matching two-port, '*o*' the output matching two-port ones and *qc* to the quasi-circulator scattering parameters.

The quasi-circulator scattering parameters are given by (13)-(16) equations.

$$S_{21}^{qc} = -j \cdot S_{21}^{td} \frac{(1 + g_{mc} Z_c) Z_0}{Z_c (1 + 2 Z_0 g_{mc}) + Z_0} \quad (13)$$

$$S_{22}^{qc} = \frac{(Z_c - Z_0) - 2 Z_0 g_{mc} Z_c}{Z_c (1 + 2 Z_0 g_{mc}) + Z_0} \quad (14)$$

$$S_{31}^{qc} = -j \cdot S_{21}^{td} \frac{Z_0 g_{mc} (Z_c - Z_0)}{Z_c (1 + 2 Z_0 g_{mc}) + Z_0} \quad (15)$$

$$S_{32}^{qc} = \left[\frac{g_{mc} Z_0 (3 Z_c - Z_0)}{(1 + Z_0 g_{mc}) Z_c} + S_{22}^{qc} \cdot \frac{g_{mc} Z_0 (Z_c - Z_0)}{(1 + Z_0 g_{mc}) Z_c} \right] \quad (16)$$

where, S_{21}^{td} represents the transmission of the divider transistor T_d and g_{mc} the transconductance of the combiner transistor. Z_0 is the reference impedance and Z_c the shunt impedance (figure 3).

With respect to an ideal SPDT switch, the matrix (12) shows that for obtaining a perfect isolation between ports (1') and (3'), S_{31}^{qc} should be zero. With $Z_c = Z_0$, this condition is achieved. Then, the matching condition at port (2') is given by:

$$S_{22}^{qc} = \frac{-g_{mc} \cdot Z_o}{1 + Z_o \cdot g_{mc}} \quad (17)$$

For achieving a perfect matching at port (2'), g_{mc} should be zero, what it means there is no transmission from port 2' to port (3').

Since this path represents the RX path, it is not accepted and then it will be necessary to trade-off between the gain in reception path and the matching at port (2'). The figure 3 shows this interdependency.

It can be seen that bigger is the gain of RX path, more bigger is the return loss of port (2').

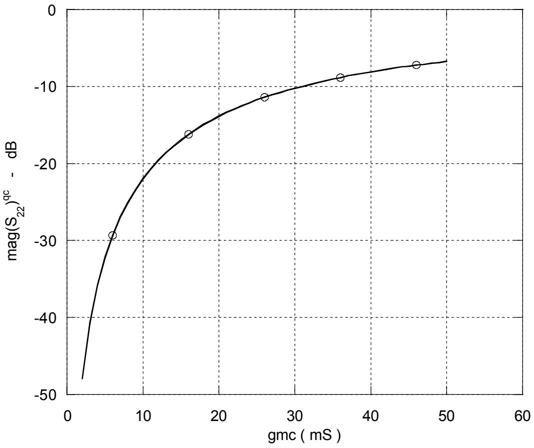

Figure 3: g_{mc} versus $S_{22\,\mathrm{dB}}^{qc}$

IV- CONCLUSION

In this paper, we proposed a SPDT front-end switch topology formed by a quasi-circulator and a SPST switch. As it is shown, the isolation of the TX/RX path is the sum of the individual isolations of each block. Then this topology has the potential applications in CMOS technology, in which the substrate losses are important. In addition this topology can provide the gain in the TX and RX paths. The next step of this work will be the realization of the SPDT switch in Integrated Circuit Technology. For this, we shall realize the simulations (scattering parameters, harmonic balance and noise figure) of the circuit with the actual components of electrical models of a specific foundry.

V-ACKNOWLEDGMENTS

The authors acknowledge the CAPES-COFECUB for the support in the form of a fellowship during the period of this research.

VI-REFERENCES

[1] T. Seshita, K. Kawakyu et al.; A 2-V Operation RF Front-End GaAs MMIC for PHS Hand-set; IEEE MTT Digest, pp. 167-170, 1998.

[2] S. Hara, T. Tokumitsu and M. Aikawa; Novel Unilateral Circuits for MMIC Circulators; IEEE Trans. on MTT, Vol. 38, October 1990, pp. 1399-1406.

[3] B. Razavi; RF Microelectronics, Upper Saddle River, Prentice Hall, Chapter 4.

[4] A. Gasmi, B. Huyart, E. Bergeault and L. Jallet; Noise and Power Optimisation of MMIC Quasi-Circulator; IEEE on MTT, Vol. 45, N° 9, September 1999, pp. 1572-1577.