Butler Matrix Based Six-port Passive Junction

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***Abstract* — In this work we propose the utilization of the Butler matrix as a six-port I/Q demodulator. The inherent symmetry of its topology allows to overcome the intrinsic amplitude and phase imbalances of the traditional approaches making it more suitable for the design of high performance six-port networks. To demonstrate the validity of the proposal a Butler matrix has been designed covering the complete UWB band and its results are compared with the traditional approaches.**

***Index Terms* — ultra-wideband (UWB), six-port I/Q demodulator, six-port receiver, Butler matrix, phase shifter, quadrature hybrid, power divider, slot-coupled lines.**

I. Introduction

Nowadays, six-port receivers are a well-known type of homodyne receiver. Since its potential as a direct conversion receiver was discovered [1], six-port receivers have become more and more relevant at microwave frequencies to be used in multiple applications: traffic safety [2], healthcare [3], near-field microscopes [4], etc.

In most of these applications the six-port passive junction is typically made up of three quadrature hybrids and a power divider. However, as it has been demonstrated in [5], the intrinsic phase differences between the input quadrature hybrid and the power divider of this circuit degrade its phase performance, even if its building elements have very low phase imbalances. To solve this limitation in [6] the architecture made up of four hybrids and a 90º phase shifter was used. This architecture allows canceling the common phase error presented by its quadrature hybrids, significantly diminishing the phase imbalance of the six-port centers. However, the extra insertion losses introduced by the phase shifter only affect one of the output channels, introducing a lack of symmetry, and causing an important amplitude imbalance between the I/Q channels.

The Butler matrix (BM) is a well-known type of passive beamforming network [7] and can be implemented using four quadrature hybrids and two 45º phase shifter (see Fig. 1(b)). A careful analysis of this circuit demonstrates that it can be used as a six-port I/Q demodulator with its centers located in π/4, 3π/4, 5π/4 and 7π/4, that is, with a fixed 45º rotation when compared with the traditional proposals. The main advantage of the BM as a six-port network (when compared with other approaches) is that this circuit is perfectly balanced in amplitude and phase, as its phase

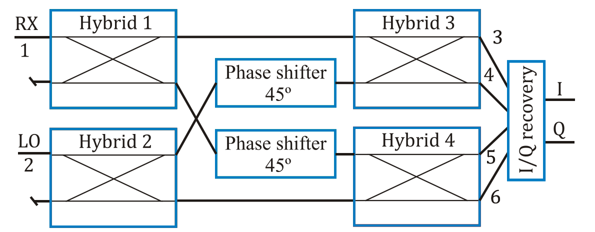

Fig.1 Block diagram of a 4x4 Butler matrix as a six-port I/Q demodulator.

shifters are equally affecting both channels.

In this work we will show that the BM can be used as a six-port passive network and we will compare its performance with previous proposals, such as the six-port network made up of four hybrids and a 90º phase shifter, when using similar building elements. Finally, we will present some measured results of a BM prototype working as a six-port network in the complete UWB band.

II. Butler matrix as a six-port I/Q demodulator

An analog six-port I/Q demodulator is comprised of a passive six-port junction and four power detectors. Assuming perfectly matched square law detectors, the four current outputs can be subtracted obtaining [6]

$$\begin{bmatrix} i_4 - i_3 \\ i_6 - i_5 \end{bmatrix} = \begin{bmatrix} \alpha_I \\ \alpha_Q \end{bmatrix} + \begin{bmatrix} \gamma_I \\ \gamma_Q \end{bmatrix} \left|\Gamma^{RX}\right|^2 + \begin{bmatrix} u_I & u_Q \\ v_I & v_Q \end{bmatrix} \begin{bmatrix} I \\ Q \end{bmatrix} \quad (1)$$

where the received symbol is $\Gamma^{RX} = I + jQ$, the DC term is $\alpha = \alpha_I + j\,\alpha_Q$, the non-linear rectified wave distortion term is $\gamma = \gamma_I + j\,\gamma_Q$, and the reference axes are u and v. These reference axes strongly depend on the six-port centers [6] and define the position of the received symbol in the complex plane as shown in Fig. 2. Any rotation of the reference axes, or amplitude and phase imbalance between them will cause a wrong demodulation of the received symbols, as shown in Fig. 2, making necessary the utilization of calibration strategies.

In a typical analog six-port I/Q demodulator the output signals of (1) allow to directly obtain the I/Q symbols. On the contrary, in the BM based six-port, as its centers ($q_i = S_{i2}/S_{i1}$) are located in π/4, 3π/4, 5π/4 and 7π/4, the six-port outputs of (1) can be rewritten as

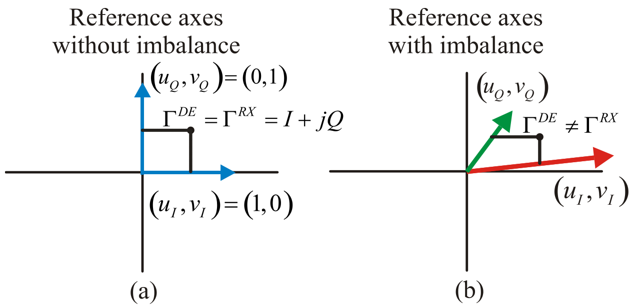

Fig.2 Reference axes of a six-port I/Q demodulator. a) Hardware without errors. b) Hardware with errors.

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\begin{aligned}
i_4 - i_3 &= \frac{P_{LO} R}{\sqrt{2}} (I - Q) \\
i_6 - i_5 &= \frac{P_{LO} R}{\sqrt{2}} (I + Q)
\end{aligned}
\tag{2}
$$

where R is the sensitivity of the power detectors. Therefore, by properly combining these outputs or just introducing a phase shift of π/4 between the RX and LO signals to locate the six-port centers in 0, π/2, π and 3π/2 the I/Q signals can be recovered.

III. SIX-PORT BUILDING ELEMENTS

Once we have shown that the BM can be used as a six-port passive network, it seems very interesting to compare its performance with other traditional architectures. In this work, we have decided to compare the performance of the proposed BM six-port of Fig. 1 with the six-port architecture made up of four hybrids and a 90º phase shifter which, as was shown previously [6], was the best known alternative to get minimum six-port phase imbalance. In order to make a fair comparison, it is important to use elements with a similar performance in both cases. Three elements are needed: i) a quadrature hybrid, ii) an 90º phase shifter, and iii) a 45º phase shifter. These circuits have designed using the multilayer stack shown in Fig. 3(a), which is composed of RO4350B substrate and RO44350B prepreg.

For the quadrature hybrid design we have decided to use a three-section slot-coupled quadrature hybrid [6], [8]. It makes use of a corrugated slot to equalize the even-odd mode phase velocities. The key features of this circuit are its low amplitude and phase imbalances, smaller than ±0.5 dB and ±0.7º in the complete UWB band.

For the phase shifters we have decided to use two-section slot-coupled structures based on the Schiffman phase shifter [9]. Using a similar design procedure as the one used in [8], and corrugated slots to equalize the even-odd modes, both circuits have been developed. The layouts of these circuits are depicted in Fig. 3. The first

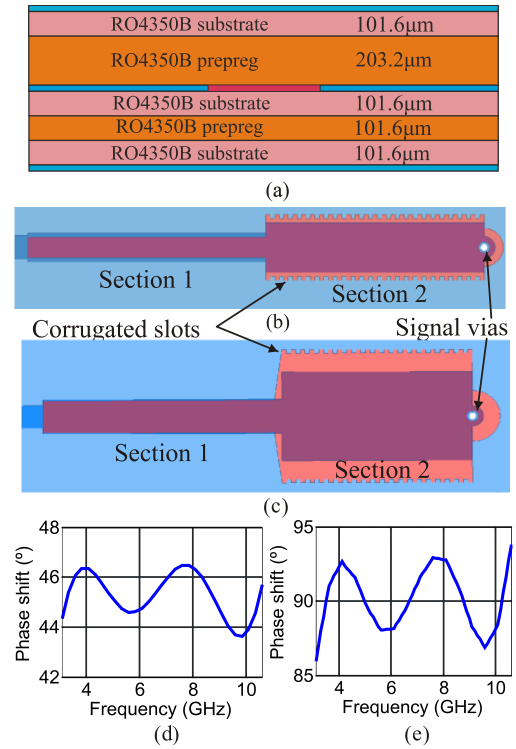

Fig.3 a) Multilayer stack used for the design of the six-port elements. b) Layout of the 45º phase shifter. c) Layout of the 90º phase shifter. d) Phase shift of the 45º phase shifter. e) Phase shift of the 90º phase shifter

one has achieved a simulated phase shift of 45±1.5º, (see Fig. 3(d)), and the second one a phase shift of 90±2.5º from 3.1 to 10.6 GHz (see Fig. 3(e)). The increased phase ripple of the 90º phase shifter is caused by the higher phase shift required and can be greatly reduce increasing the number of sections [7].

IV. PERFORMANCE COMPARISON OF THE DIFFERENT SIX-PORT NETWORKS

Once the building elements have been presented, in this section we will compare the performance of the six-port architectures. In general, both architectures have exhibited good results in simulation, with a return loss better than 24 dB, an RX-LO isolation higher than 27 dB, and six-port centers with an amplitude and a phase imbalances lower than ±1 dB and ±4º, respectively. Even though both architectures seem to be equally balanced, there is an important difference between them: the imbalance between the I/Q channels. This error is caused by the imbalance between the references axes v/u, and cannot be directly assessed with the six-port centers because of their normalization. As we can see in Fig. 4(a), both circuits achieve the quadrature condition between the

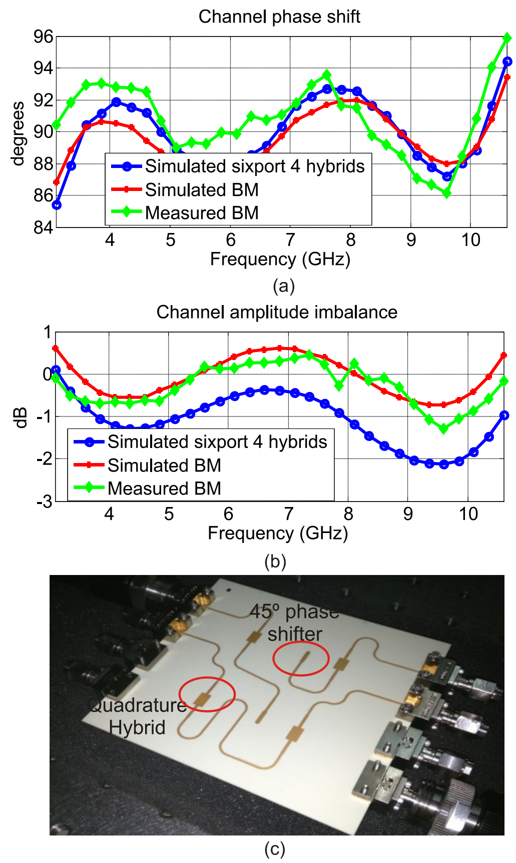

Fig.4 a) Phase shift between the I/Q channels $\measuredangle(v/u)$ for both six-port networks. b) Amplitude imbalance between the I/Q channels $|v/u|$ for both six-port networks. c) Photograph of the fabricated BM.

I/Q channels with a phase error lower than ±4º. However, the six-port network made up of four hybrids and a 90º phase shifter exhibits an important amplitude imbalance of 2 dB caused by the lack of symmetry introduced by the 90º phase shifter. This high imbalance does not appear in the BM (lower than ±1 dB), because this circuit has a perfectly symmetrical structure, which makes use of two 45º phase shifter, thus balancing in amplitude the I/Q channels. This lack of symmetry could be also solved using the classical six-port junction made up of three quadrature hybrids and a power divider. However, as it was demonstrated in [6], phase shifter based six-port architectures can outperform the classical one when using high performance phase shifters.

The BM has been fabricated (see Fig. 4(c)) obtaining good results with an amplitude and phase imbalance around ±1 dB and ±4º in most part of the UWB band (see Fig. 4). Furthermore, its phase imbalance can be greatly improved using higher order phase shifters, as it has been previously demonstrated in [6].

Conclusion

In this work, we have shown that the BM can be used as a well-balanced six-port I/Q demodulator thanks to the symmetry of its topology. This circuit allows to greatly reduce the imbalances of the traditional approaches when using the same building elements, what makes the BM very interesting for the design of high performance six-port I/Q demodulators. A prototype has been fabricated covering the complete UWB band with an amplitude and phase imbalance between the I/Q channels around ±1 dB and ±4º, which are in agreement with the simulated results.

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