A Novel Reconfigurable Coupler for Intelligent SOP RF Front-ends

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Abstract – **A novel class of planar reconfigurable directional couplers for intelligent System on Package (SOP) RF front-ends is presented. Reconfigurability is obtained by modifying the electrical parameters of the coupled lines so as to tune the coupling ratio. RF switches such as MEMS or PIN diodes can be used to enable a wide range of reconfigurability in a very compact and low-loss device. The performance and the limitations of the coupler are discussed and design equations are provided. A hardwired prototype in microstrip technology has been manufactured. The novel concept introduced, however, is technology independent so that the reconfigurable coupler can be fabricated in microstrip, stripline or coplanar configurations.**

I. INTRODUCTION

During the past years reconfigurable devices have received growing attention, due to the availability of high performance switches, the latter being enabled by the recent development of MEMS switches as well as by improved low-loss and low-capacitance RF PIN diodes. Tunable antennas [1]-[2], tunable filters [3] or phase shifters [4] are just a few classical examples among many proposed devices belonging to the large class of reconfigurable systems. These devices can exist in digital as well as in analog configuration, the main feature being the capability to adapt their state depending on the need or on the environmental condition (e.g. antennas). In other words, one single tunable device is capable of multiple operating conditions, reducing therefore the size, the weight, the cost, and substantially improving the overall performances.

In this paper, a new class of devices is proposed: a coupler with a digital reconfiguration of the coupling ratio. In the past, a similar device has been presented in [5], but the tunability was intended for the operating frequency band. In [6] and [7] a reconfigurable coupler was proposed in waveguide technology, while in [8] a planar analog reconfigurable coupler employing varactors has been presented. In [9]-[11] different schemes of reconfigurable T-junctions have been proposed. However, even though in some applications the coupler plays the same role as a power divider, there are many others where these devices cannot be interchanged. Accordingly, the new concept, herein introduced, shows unique features: the coupling ratio can be tuned (within certain limits) by using only two switches for each bit, thus maintaining very low losses. Additionally, a very good compactness is achieved, for the overall size of the coupler is approximately the same as a standard not-tunable one –not including the bias network and DC line required for the control of the switches. The proposed device essentially consists of three coupled lines in which two or more switches are placed along two of them. Some of the possible applications are:

- Amplitude weighting control of antenna arrays: this is typically made by way of attenuators, which reduce the efficiency and increase the power consumption. By using, e.g., a reconfigurable Blass matrix it is possible to reconfigure the radiation pattern of a multi-beam antenna with no substantial increase of power losses.
- Tunable directional filters: by cascading multiple sections of the couplers, it is possible to achieve a directional filtering which can be tuned by varying the coupling level of each segment.
- Reconfigurable baluns in bandwidth: the coupler-based baluns have a bandwidth which is dependent on the coupling ratio.

In the following, the theory used for the design and a the results of a hardwired microstrip demonstrator are presented.

II. THEORY

The operation of the proposed reconfigurable device is based on the electrical properties of two asymmetric coupled lines, the theory thereof being discussed in [12]. In [13], the ideal backward directional coupler with asymmetrical coupled lines has been considered by Cristal, who additionally provided the following formulas illustrating the relationship between physical line parameters (C_a, C_b and C_{ab}), coupling coefficient k and terminating admittances Ga and Gb.

$$\frac{C_a}{\varepsilon} = \frac{376.7}{\sqrt{\varepsilon_r}} \cdot \left(\frac{G_a - k(G_a G_b)}{\sqrt{1-k^2}} \right) \tag{1}$$

$$\frac{C_b}{\varepsilon} = \frac{376.7}{\sqrt{\varepsilon_r}} \cdot \left(\frac{G_b - k(G_a G_b)}{\sqrt{1-k^2}} \right) \tag{2}$$

$$\frac{C_{ab}}{\varepsilon} = \frac{376.7}{\sqrt{\varepsilon_r}} \cdot \frac{k(G_a G_b)}{\sqrt{1-k^2}} \tag{3}$$

The reconfigurable coupler toggles its state between two configurations, shown in Fig. 2-3. When the switches are "ON" – ideally a short circuit (state 1) –, the middle line is shunted to one of the two side lines. A strong coupling is therefore obtained by means of the proximity of line 1 and line 2. On the other hand, when the switches are "OFF" (state 2), the middle line is floating and, being line 1 and line 3 farther, the coupling is weaker.

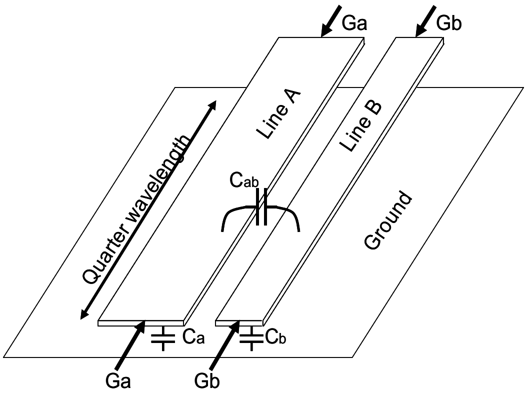

Fig.1. Two line asymmetrical coupler. C_a, C_b and C_{ab} = capacitance per unit length. Ga, Gb = terminating admittances.

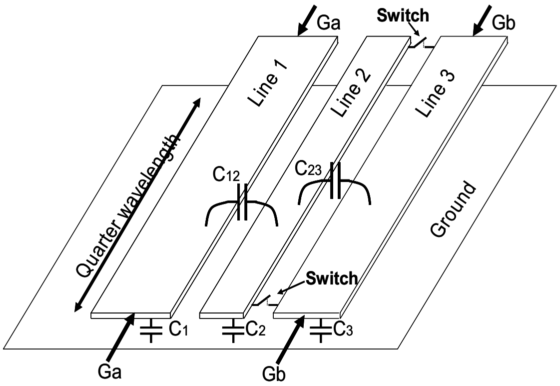

Fig.2. Three-line asymmetrical coupler, scheme proposed.

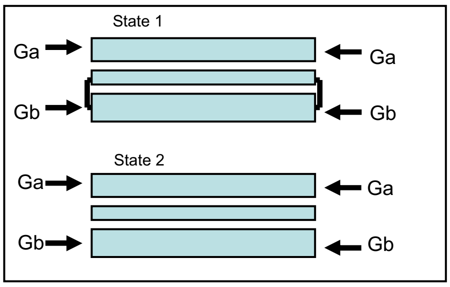

Fig.3. The two basic states corresponding to switches on (state 1) and off (state 2) of the coupler shown in Fig. 2.

An ideal reconfigurable coupler should present in both states a perfect matching and an infinite directivity. These parameters depend on the geometry of the lines and on the terminating admittances. The formulas in (1)-(3) can be exactly applied to find the physical characteristics of the lines of an ideal coupler with perfect matching and infinite directivity, given the desired admittance terminations and coupling. In order to use these formulas for the reconfigurable coupler of Fig.2, two terminating admittances (*Ga* and *Gb*) must be chosen a-priori, along with two desired coupling coefficients k_1 and k_2. Once the latter parameters have been specified, the formulas give six different line parameters: C_{a1}, C_{b1}, C_{ab1}, C_{a2}, C_{b2}, and C_{ab2}.

In general, C_{a1} is different from C_{a2}. Nonetheless, the structure of Fig. 2 requires:

$$
\begin{aligned}
C_{a1} &= C_{a2} = C_1 \\
C_{ab1} &= C_{12} \\
C_{ab2} &= \left(\frac{1}{C_{12}} + \frac{1}{C_{23}} \right)^{-1} \\
C_{b1} &= C_3 \\
C_{b2} &= C_2 + C_3
\end{aligned}
\tag{4}
$$

When the above constraints are superimposed the formulas in (1)-(3) give no feasible solution for any realistic value of Ga and Gb and for any coupling coefficient k_1 and k_2. However, if a finite directivity as well as a reasonable mismatching can be tolerated, it is still possible to find some solutions for the terminating admittances and coupling ratio, since the above equations can still be applied with a small approximation error. In the present work, this procedure has been performed by an optimization algorithm (iterative optimization algorithm, [14]).

Observe that the algorithm must also optimize the terminating admittances in order to obtain the required coupling coefficients k_1 and k_2. They are therefore design parameters, conversely to the Cristal's formulas (3) where they are specifications for the design. If different admittance levels are required, a matching network must be added to the ports of the coupler.

III. Microstrip Design

The basic design shown in Fig.2 can be cascaded in order to increase the number of states of the same device provided that the overall end-to-end distance is a quarter of a wavelength. Thus, it is possible to design reconfigurable couplers with any number of bits and different coupling levels. Observe that each bit is enabled by two switches which are simultaneously "ON" or "OFF". Practical limitations therefore occur when considering the area required to accommodate the switches and the bias network. This limits the maximum number of bits to 3 or 4 (corresponding to 6/8 switches), depending on the technology and frequency band used.

In order to demonstrate the concept introduced, one 2-bit reconfigurable microstrip coupler has been designed (Fig.4) according to the specs in Tab.5, and measured (Fig.6) at the central frequency of 5.2 GHz. Although the formulas of Cristal are intended for homogeneous media, the low permittivity used for the substrate (Rogers Duroid 5880, r=2.2) causes only a small discrepancy with respect to the theoretical case. If a higher permittivity is employed, the coupler results in a poorer directivity, though optimization or compensation can still be performed [14]-[15].

IV. Measured Results

The 2-bit coupler has been fabricated and tested. The switches have been replaced by hardwire connections (ideal short/open); therefore four samples, corresponding to the four possible states, have been constructed. In Fig. 7 it is possible to see one of the boards.

The results, shown in Fig. 8-9, show a directivity of more than 15 dB and a good matching with reflection losses of less than -15 dB in the operating frequency band. The coupling ratio is reconfigured with approximately the same values as the full-wave simulation of Fig. 6. The poorer mismatch and directivity is attributable to fabrication tolerances. The power losses have been calculated to be less than 0.6 dB. If PIN diodes are added, the losses are expected to increase to about 1.5 dB in the worst case (all switches on, state 1), and further less if MEMS are used.

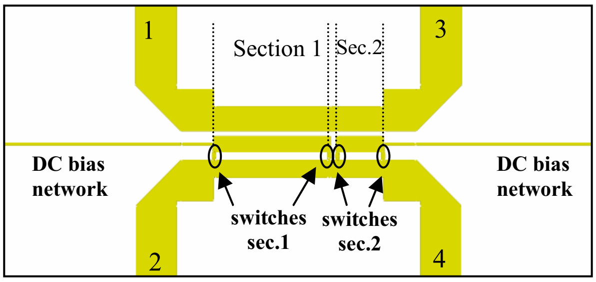

Fig.4. 2-bits reconfigurable coupler

	Switches section 1	Switches section 2	Expected Coupling
State 1	ON	ON	-8 dB
State 2	ON	OFF	-10 dB
State 3	OFF	ON	-12.5 dB
State 4	OFF	OFF	-16 dB

Tab.5. List of the different states of the coupler, and associated expected coupling (circuital simulation).

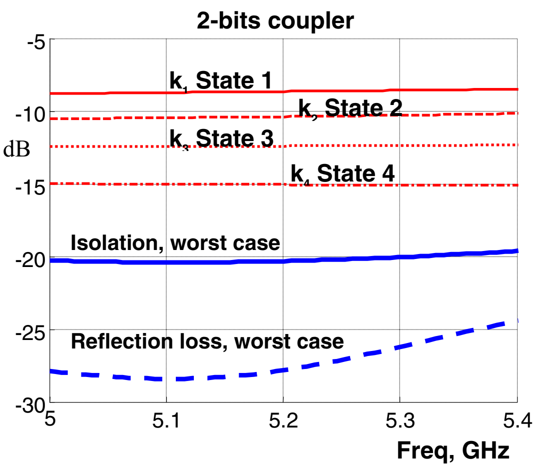

Fig.6. Results (full-wave simulations) of the coupler of Fig.4.

k1 state 1 = -8 dB; k2 state 2 = -10.5 dB

k3 state 3 = -12.5 dB; k4 state 2 = -15 dB

Reflection losses and isolation: <-20 dB

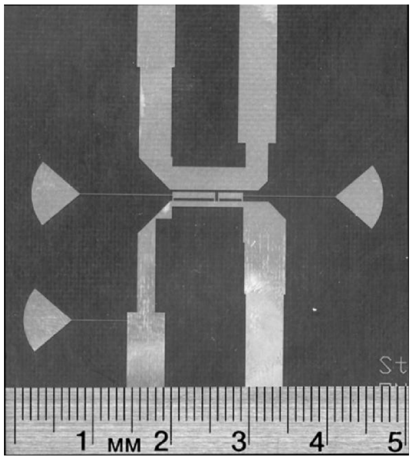

Fig.7. Microstrip reconfigurable coupler, 2-bits, realization of the state 1 (all switches on). Size: 4.5 X 5 cm.
Substrate: Duroid 5880, Er 2.2, tickness 1.575 mm.

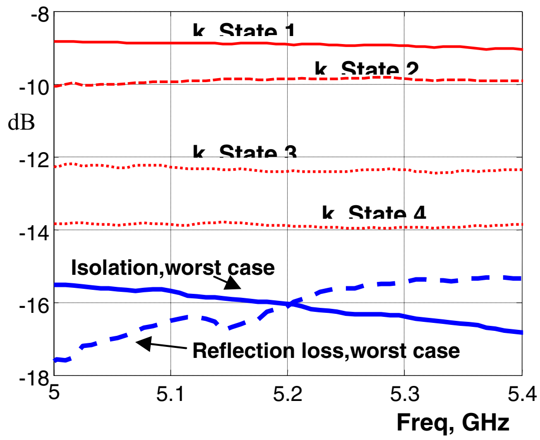

Fig.8. Measured results in the band of interest (5 to 5.4 GHz). Coupling ratio: -8.5, -10, -12, -14 dB. Reflection losses (dotted line): <-15 dB. Isolation (solid line): <-15 dB.

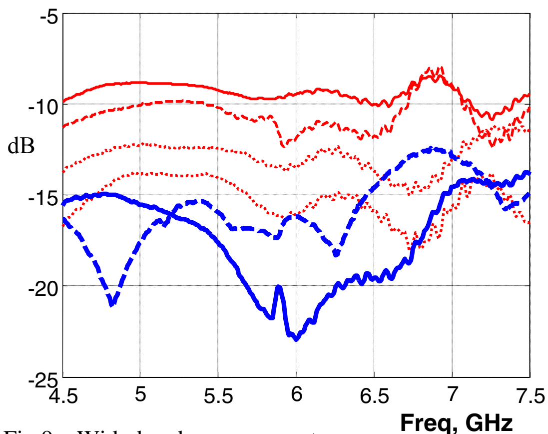

Fig.9. Wide-band measurements.

V. CONCLUSIONS

A novel reconfigurable class of couplers has been proposed. A microstrip demonstrator of a 2-bit device has been fabricated, showing low loss, good matching, directivity, and a coupling ratio tunable from -8.5 to 14 dB. The inclusion of switches is expected to be reasonably straightforward. The compactness of the device makes it suitable especially for intelligent SOP

RF front-ends, where size and power losses are issues of fundamental importance. The design indeed proposed can be fabricated in any planar technology; it is therefore possible to be integrated with other devices such as filters, antennas or active components.

Future developments will pertain to the inclusion of the switches, the design of a 3 bit version of the coupler, and the employment of different technologies, such as coplanar or multilayer.

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