Novel Broadband Nonreciprocal 180° Phase-Shifter

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Abstract — **In this contribution, a novel broadband 180° phase shifter, realized in 0.5 µm GaN HEMT technology developed by SELEX Sistemi Integrati, is presented. This new topology is based on the combination of two directive three-port elements with a four-port phase-shifting network: the proposed MMIC is featured by an average zero insertion loss, 180°±2° differential phase-shift and good port matching over the 3-7GHz operating bandwidth. The MMIC size is 3.5x3.4 mm^2.**

NRPS; Phase Shifter; GaN MMIC; Distributed Amplifier; Broadband; Non-Reciprocal; Circulator; Quasi-Circulator.

I. INTRODUCTION

Circulators are three-port non-reciprocal elements typically used to separate incident and reflected waves from a given termination. The incident signal circulates in clockwise or counter-clockwise direction toward the adjacent port; in the reverse direction, ideally no signals flows. Isolators operate in a similar manner, being two-port elements. Circulators and isolators are crucial functional blocks used in a variety of microwave systems, including satellites' payload chains, communications receivers/transmitters, frequency scaling modules. They may be used as well to implement new functionalities, such as reflection phase shifters and reflection amplifiers.

Passive devices are typically used to obtain the non-reciprocal behavior: ferrite materials are used, shaped in particular forms in waveguide, microstrip or stripline structures, or used as substrates [1]. Passive devices offer a low insertion loss, do not dissipate nor require DC power and handle high power signals. On the other hand, passive structures are featured by large size, narrow operating bandwidth and the needs of a magnetic bias. More importantly, it is not possible to integrate a passive isolator/circulator within a MMIC circuit.

Recently, a remarkable interest is growing on active structures: active isolators are achievable [2, 3] exploiting the behavior of properly connected transistors. Several active circulator topologies can be envisaged. Among the latter ones, an interesting class is represented by the structures composed by a *non-reciprocal phase shifter* (NRPS) [4, 5, 6], and they are selected for the present work. NRPSs are two-port devices ideally providing a very low insertion loss, good matching on both ports and the requested differential phase shift between signals flowing in opposite directions. NRPSs can form new architectures for circulators or isolators or translate passive solutions into active ones, as the passive isolator described in [7]. A NRPS exhibiting an arbitrary differential phase shift can be used to design new isolator or circulator topologies. However, all of the active devices presented to date for this purpose are realized in GaAs. In this case the resulting structure cannot handle high power signals: with the aim to realize a robust chip for communication systems withstanding high power signals, GaN/SiC technology is adopted in this contribution. The resulting NRPS is featured by broadband operation, as compared to the two topologies already presented in open literature, exhibiting a 10% fractional bandwidth [8] or a maximum 22% [9].

II. SYSTEM ARCHITECTURE

The NRPS system is a two-port bidirectional network exhibiting the same (ideally zero) insertion loss in both directions while maintaining different insertion phases. The phase difference between the two paths, designed to be 180°, represents the actual phase-shift necessary to realize the abovementioned isolating or circulating structures. This new topology is based on the integration of two distinct functionalities: signal routing and delay. Such an integration can be practically implemented by the combination of two directive three port elements with a four port phase-shifting network, as it will be shown in the following.

A different phase-shifter has been previously presented by the same authors [9]. This circuit, although successfully implementing the phase-shifting operation, suffers from inherent bandwidth limitations; these restrictions are mainly due to the intrinsic narrowband performance of the Wilkinson power splitter/combiner adopted as routing element.

In order to overcome the abovementioned bandwidth limitations, the novel topology uses a directive distributed amplifier as broadband routing element (Fig.1a) and a four port broadband phase-shifting section based on all-pass network (APN) band-pass filter (BPF) arrangement (Fig.1b). Directive distributed amplifier, as reported in Fig.1a, is intended as a three port network whose detailed design procedure will be illustrated in the next section. Referring to Fig.1a, the signal flows from input (labeled as Port 1) to forward output (labeled as Port 2), boosted by the intrinsic amplifying behavior of the circuit, but cannot propagate towards the reverse output (labeled as Port 3) because of its inherent directivity; again, signal flows along the passive drain line, between Port 2 and 3, in both directions but cannot propagate towards Port 1, as a consequence of the active devices non-reciprocal behavior.

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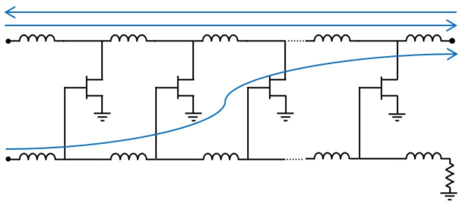
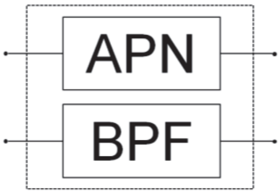


(a)



(b)

Figure 1. NRPS building blocks: (a) directive distributed amplifier; (b) four port phase shifting network.

Keeping in mind the aforementioned behavior and with reference to Fig.2, the signal at Port A flows along the drain line of the left amplifier, passing through the upper path of the filtering (phase-shifting) section and finally emerges at Port B, after being amplified by the right directive amplifier (red arrow); on the other hand, a signal at Port B flows along the drain line of the right amplifier, passing through the lower path of the filtering (phase-shifting) section and finally emerges at Port A, amplified by the left directive amplifier (green arrow). A signal flowing in the structure therefore undergoes different phase shifts, depending on its direction: the phase difference between such phase shifts, kept as constant as possible over the entire operating bandwidth by the proper choice of the filtering section, is the target design differential phase shift.

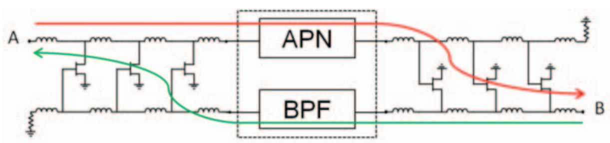


Figure 2. NRPS working principle.

III. System Design

As already mentioned the NRPS operating bandwidth is broadened by the introduction of circuit topologies based on intrinsically broadband building blocks. The design procedure of such subsystems, implementing signal routing and delaying functionalities, will be illustrated in the following.

A. Directive Distributed Amplifier

Distributed amplifiers represent a fairly old and well known concept [10-11] and are usually employed in a variety of applications where ultra-broadband performance are intended as a fundamental prerogative.

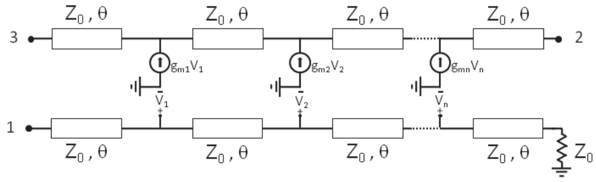


Figure 3. Distributed amplifier simplified equivalent circuit.

Considering an extremely simplified model, as depicted in Fig.3, two gains can be defined: forward gain (G_{fwd}), between Port 1 and 2, and reverse gain (G_{rev}), between Port 1 and 3, whose analytical expressions, according to multi-element directional coupler theory [1][12], are reported in the following:

$$G_{fwd} = \left| -\frac{1}{2} Z_0 e^{-j\theta(\omega)N} \sum_{i=1}^{N} g_{mi} \right|^2 = \left| \frac{1}{2} Z_0 \sum_{i=1}^{N} g_{mi} \right|^2 \quad (1)$$

$$G_{rev} = \left| -\frac{1}{2} Z_0 \sum_{i=1}^{N} g_{mi} e^{-j2\theta(\omega)N} \right|^2 = \left| \frac{1}{2} Z_0 F(\omega) \right|^2 \quad (2)$$

where F is the array factor. Directivity can be defined in this context as the ratio between forward and reverse gain and thus, referring to (1) and (2), it exhibits a frequency behavior merely dependent to the latter, being the former frequency-independent:

$$D = \frac{G_{fwd}}{G_{rev}} = \frac{\left| \sum_{i=1}^{N} g_{mi} \right|^2}{\left| F(\omega) \right|^2} \quad (3)$$

Controlling the array factor allows to obtain the desired directivity: in order to achieve a wideband directivity design, array factor has to be made proportional to a Chebyshev polynomial by properly selecting devices' transconductances g_{mi}. Different considerations about achievable directivity, operating bandwidth and area occupation finally led to a structure composed by three elementary cells (including three active devices).

For amplifier proper operation, it is mandatory to set 90° as the electrical length of the elementary cell at center frequency, that is the maximum phase shift achievable by a single T-section made up of lumped elements [13]. To improve amplifier frequency response, three elementary cells, made up by an active T-section (including the active device) and a dummy T-section (including capacitance) were employed.

Actual transconductance values were selected by setting the desired value of directivity (14dB), bandwidth (3-7GHz) and imposing 5dB forward gain as the best compromise to avoid any stability issue for the complete system and to compensate for drain line and phase shifting section losses. These values finally resulted in g_{m1}=g_{m3}=21mS, g_{m2}=28mS: their practical implementation was performed by choosing device periphery to ensure a reasonable power handling level and then inserting the proper series capacitor on FET gates. In Fig.4 forward and reverse gain, related to an ideal structure as in Fig.3 and considering the abovementioned transconductance values, are reported.

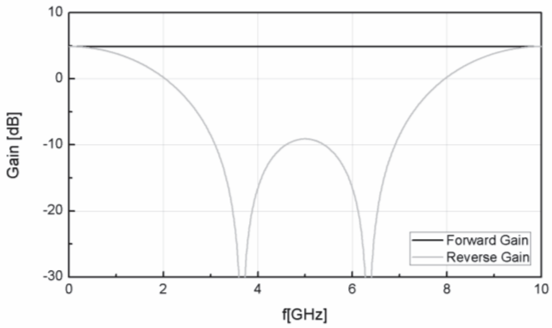


Figure 4. Directive distributed amplifiers ideal gain

B. *Phase-Shifting Section*

As already stated, the filtering section is the subsystem in charge of the synthesis of the desired value of differential phase shift and whose actual design mostly affects the entire system performance. By the proper choice of filtering section, different values of differential phase shift can be achieved: even limiting the attention to 180° differential phase shift, different distributed and lumped switched network examples can be found. In [14] as an example, a distributed implementation is illustrated featuring pretty good phase shift and magnitude unbalance but implying an excessive amount of area occupation. In [15] and [16] two different lumped implementations are proposed, respectively based on all-pass/all-pass network and all-pass/band-pass arrangements. The latter solution, reported in Fig.4, seems to guarantee a significantly better level of phase deviation all over the bandwidth together with a circuit topology more suitable for active device biasing purposes.

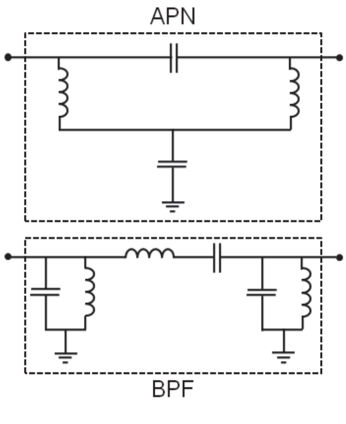


Figure 5a. APN/BPF phase shifting section.

IV. Test Vehicle Design and Expected Results

A monolithic test vehicle has been designed to verify the feasibility of the proposed topology and to evaluate its performance. The broadband NRPS has been designed using the 0.5 µm GaN/SiC HEMT process developed by SELEX Sistemi Integrati, featuring Idss = 600 mA/mm at Vdd = 25 V. The target operating bandwidth occupies more than one octave, i.e. 3-7 GHz. Each active device is featured by 4x75 µm Gate periphery and biased at $V_D = 25$ V, $I_D = 50\%\ I_{dss}$.

The layout of the designed broadband NRPS is presented in Fig.5b.Chip size is 3.5 x 3.4 mm^2. The g_m modulation, needed to obtain the desired amplifier directivity level, is achieved by tapering the gate capacitors; this implies the use of bypass resistances for biasing FETs. Ports A and B are visible on the upper left and right borders respectively. Bias pads are placed on the upper and lower sides of the MMIC.

The four-port phase shifting network is noticeable between the two distributed amplifiers: the APN and the BPF are on the upper and lower sides respectively. Classical APN structure has been modified to bias the drain of the left distributed amplifier; the BPF circuit topology has instead been exploited in order to bias the gate of the left distributed amplifier and the drain of the other one. The remaining gate of the right distributed amplifier has been biased by the termination resistor directly connected to the bias pad.

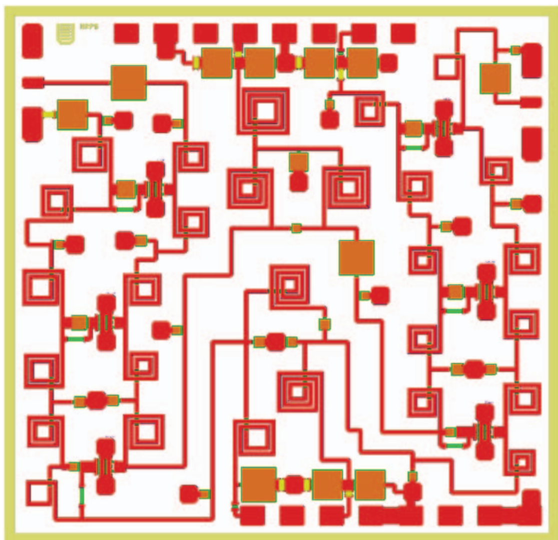


Fig. 5b. Broadband active NRPS' layout here proposed.

As can be noticed form Fig.6, the resulting port matching is better than 12 dB over the 3-7 GHz frequency range. In Fig. 7, the insertion gain is depicted: a variation of ±1 dB around the null value is noticeable.

Most important NRPS' figure-of-merit is the differential phase shift: the resulting performance of the designed MMIC is remarkably good, resulting in a 180°÷2° differential phase shift over the entire 3-7 GHz frequency band.

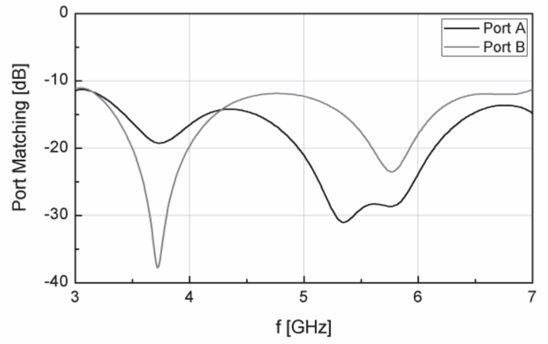


Fig. 6. Broadband active NRPS' port matching.

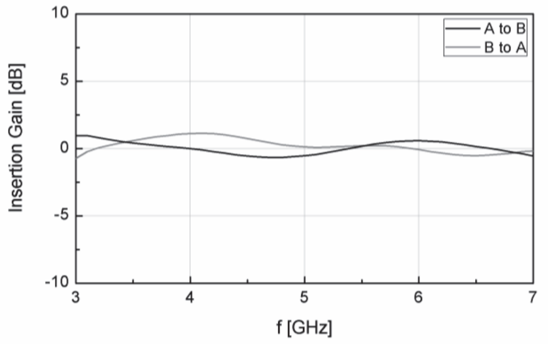


Fig. 7. Broadband active NRPS' insertion gain.

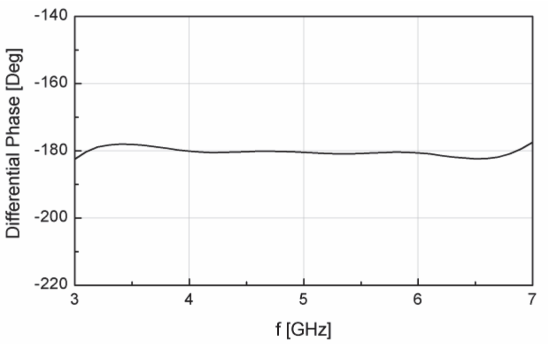


Fig. 8. Broadband active NRPS' differential phase shift.

V. CONCLUSION

In this contribution a novel monolithic Non Reciprocal Phase Shifter has been proposed and extensively illustrated. This new topology, based on the integration of signal routing and delay, uses a directive distributed amplifier as broadband routing element and an all-pass/band-pass network as broadband phase-shifting section. The design flow of a compact monolithic GaN demonstrator has been described together with the resulting expected performance. The proposed structure is featured by an average zero insertion loss, 180°±2° differential phase-shift and good port matching over the 3-7GHz operating bandwidth. To the authors' knowledge this is the first implementation of such a type of phase shifter.

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