

Novel Active Distributed Circulator

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Abstract – In this contribution a novel distributed circulator topology based on the integration of three active quasi-circulators is proposed. A 3 by 3 mm² monolithic test vehicle was designed to verify the effectiveness of the approach. The MMIC demonstrator exhibits a return loss better than 10 dB while insertion loss and isolation are better than 1 dB and 15 dB respectively. Achieved operating bandwidth is 40% around the 6 GHz central frequency.

Index Terms – Distributed amplifiers, active circulators, MMIC, C-band.

I. INTRODUCTION

Passive circulators are typically narrowband structures because of their narrow non-reciprocal behavior. To overcome size, weight and magnetic bias issues, several active circulators were proposed.

A first BJT-based circulator with very high isolation (40 dB) was firstly proposed, operating in the 30 Hz – 30 kHz frequency range [1]. Subsequently, the same architecture was modified replacing BJT with FET devices. In these cases a frequency range from 0.2 to 10 GHz was achieved but insertion loss ranges from 3 to 8 dB [2, 3, 4].

On the other hand, very low insertion loss (0.7 dB) was achieved connecting three isolators by means of three Wilkinson power dividers [5]. This approach provides 15 dB isolation but a narrowband frequency behavior, restricted to 11.5% operating bandwidth. To broaden the bandwidth, three Lange coupler were finally used to replace the Wilkinson dividers [6], thus achieving a noticeable bandwidth improvement (40% around the 5 GHz central frequency), better isolation (17 dB) and insertion loss (± 0.3 dB).

Unfortunately, the couplers size leads to a very big structure at such operating frequencies.

By means of non-reciprocal phase shifters [7, 8, 9, 10], it is possible to perform circulation functionalities. Referring to complete circulation (excluding quasi-circulators), a delta architecture exhibits 15 dB isolation and 1 dB insertion loss in a 15% operating bandwidth centered at 9.1 GHz.

In this contribution, a distributed active circulator is proposed to improve chip area occupation and bandwidth performance, compared to the previous circuits. To achieve these targets, the intrinsic distributed amplifiers' behavior has been exploited.

II. PROPOSED TOPOLOGY

As already stated, narrowband frequency response is the main factor limiting the use of active devices in the realization of complete circulating structures. The need for circuit topologies, intrinsically featured by a broadband frequency response, guided the research toward the use of distributed approaches.

A distributed amplifier can be viewed as a three port network, when access to the drain line reverse termination is provided (Fig 1).

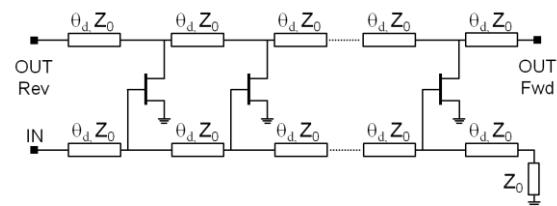


Fig.1. Distributed amplifier as a three port network.

In recent years, different contributions demonstrated the feasibility of quasi-circulating structures by means of properly designed distributed amplifiers, namely directive distributed amplifiers (DDA) [11]. This kind of amplifier can be modeled using an extremely simplified equivalent circuit, as reported in Fig 2, where a number of voltage-controlled current sources is connected by ideal transmission lines.

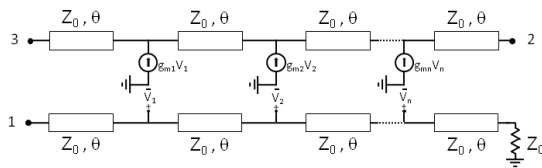


Fig.2. Distributed amplifier simplified model.

Considering this model, two gains can be defined: forward gain (G_F), between Port 1 and 2, and reverse gain (G_R), between Port 1 and 3, whose analytical expressions, according to multi-element directional coupler theory [11,12], are reported in the following:

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

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

In equation (2) 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 on the reverse gain, being the forward one frequency- independent:

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

Controlling the array factor allows to obtain the desired directivity: in order to achieve a

wideband directivity design, the array factor has to be shaped making use of a Chebyshev approach, by properly selecting devices' transconductances g_{mi} and sizing transmission lines as quarter-wavelength structures [12]. When a perfectly matched and lossless structure is considered, as the one depicted in Fig 2, the S-parameters matrix of the circuit can be inferred:

$$S_{QC} = \begin{pmatrix} 0 & 0 & 0 \\ G_F & 0 & 1 \\ G_R & 1 & 0 \end{pmatrix} \quad (4)$$

The expression in (4) clearly evidences the quasi-circulating properties of DDA.

The novel circuit topology, herein proposed, exploits the properties of three DDAs properly connected to build up a complete circulating structure. More in detail, referring to Fig 3, signal entering port 1 passes through the drain line of amplifier A and emerges amplified by the amplifier B at port 2; otherwise, the signal cannot reach port 3 (amplifier C) by the effect of the inherent directivity of amplifier B. The same argument can be obviously extended for the signals entering ports 2 and 3.

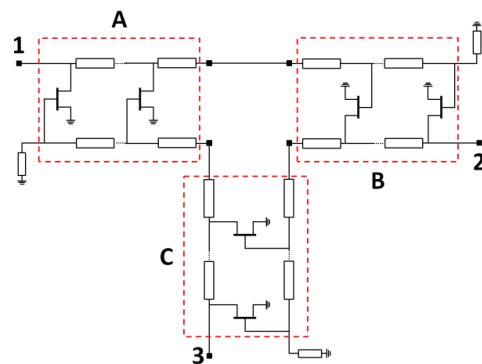


Fig.3. Presented distributed circulator topology.

Again considering perfectly matched and lossless structures, S-parameters matrix of the complete circuit can be inferred:



$$S_C = \begin{pmatrix} G_R^2 \cdot G_F & G_R \cdot G_F & G_F \\ G_F & G_R^2 \cdot G_F & G_R \cdot G_F \\ G_R \cdot G_F & G_F & G_R^2 \cdot G_F \end{pmatrix} \quad (5)$$

If the amplifier has been properly designed in order to exhibit a unitary gain (in linear scale) and a directivity D , the matrix in (5) reduces to:

$$S_C = \begin{pmatrix} D^{-2} & D^{-1} & 1 \\ 1 & D^{-2} & D^{-1} \\ D^{-1} & 1 & D^{-2} \end{pmatrix} \quad (6)$$

When the directivity D tends to infinity (i.e. null reverse gain), matrix in (6) finally assumes the typical expression for ideal circulators:

$$S_I = \begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix} \quad (7)$$

III. MMIC TEST VEHICLE DESIGN

A monolithic test vehicle has been designed to verify the feasibility of the proposed topology and to evaluate its performance. The broadband distributed circulator has been designed using the 0.18 μm GaAs pseudomorphic HEMT process developed by OMMIC.

The first step in circuit design is the choice of the number of stages composing the single DDA: different considerations about achievable directivity, operating bandwidth and area occupation finally led to a structure composed by three elementary stages.

Actual transconductance values were selected by setting the desired value of directivity (20 dB), bandwidth (5-7 GHz) and imposing 1 dB forward gain as the best compromise to avoid any stability issue for the complete system and to compensate for drain line losses. These values

finally resulted in $g_{m1}=g_{m3}=20 \text{ mS}$ and $g_{m2}=30 \text{ mS}$: their practical implementation was achieved by choosing device periphery according to the graph in Fig. 4 showing, for a fixed bias condition ($V_{DS}=2 \text{ V}$, $V_{GS}=0 \text{ V}$), the value of transconductance as a function of the device periphery itself. Selected devices' geometries are $2 \times 18 \mu\text{m}$ and $2 \times 32 \mu\text{m}$ respectively.

Once devices' periphery has been selected, FET parasitic capacitances have to be determined in order to accurately synthesize the quarter wavelength line required for the circuit proper operation. The artificial transmission line can be obtained by means of three reactive elements arranged to form a lumped-element T-section. To obtain the desired electrical length and to equalize gate and drain line phase velocities, an additive shunt capacitor has to be inserted on the gate and drain nodes.

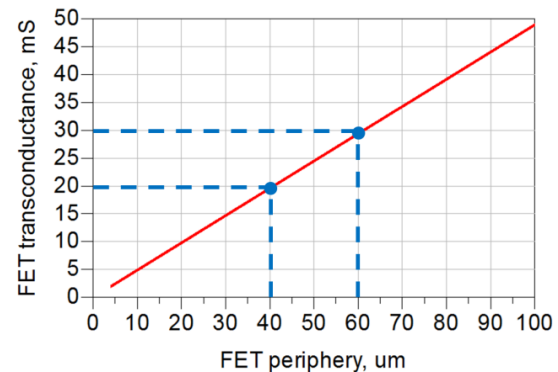


Fig.4. FET transconductance as a function of FET periphery.

IV. EXPECTED RESULTS

The layout of the designed distributed circulator is presented in Fig. 5: the monolithic test vehicle exhibits a total area occupation of about 9 mm^2 ($3 \text{ mm} \times 3 \text{ mm}$). The presence of three RF ports is noticeable on the left, right and lower border of the MMIC, whereas DC pad for drain bias are placed on the remaining upper border (FETs' gates are self biased to 0 V). The circuit exhibits a total DC power consumption of 180 mW.

Resulting simulated performance in terms of port matching is visible in Fig.6 where a return loss better than 10 dB in the 4.5 GHz-7.5 GHz frequency range is reported: as it can be noted, operating bandwidth is about 40 % around 6 GHz center frequency.

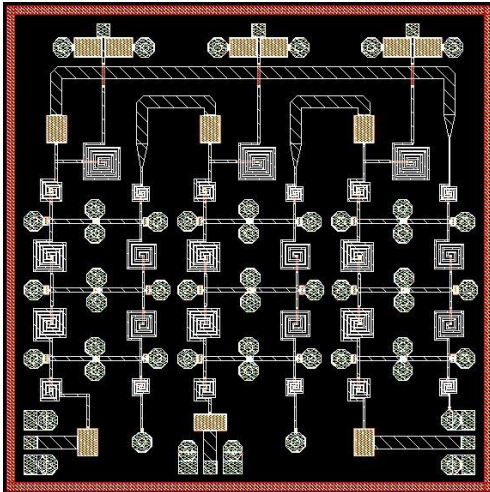


Fig.5. Layout view of the designed MMIC test vehicle.

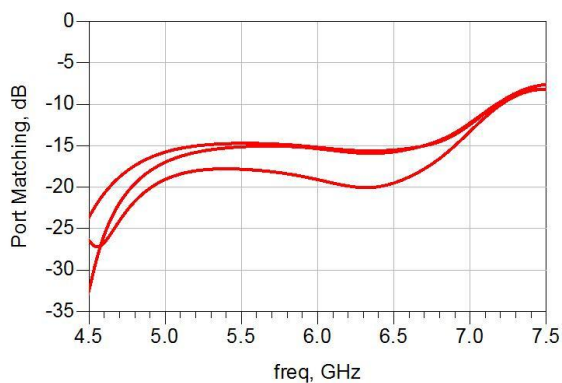


Fig.6. Distributed circulator port matching.

In Fig. 7 and Fig. 8 transmission parameters relative to desired and unwanted paths are respectively depicted. Looking at the first graph an insertion loss better than 2 dB can be remarked over the entire operating band for the allowed paths (S_{21} , S_{32} , S_{13}). On the other hand,

insertion loss higher than 15 dB is guaranteed for the forbidden paths (S_{12} , S_{23} , S_{31}).

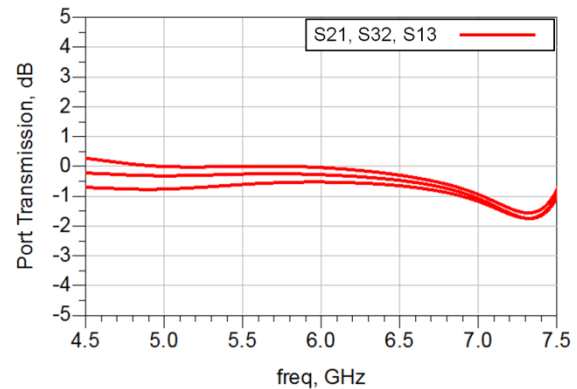


Fig.7. Transmission parameters of the allowed paths.

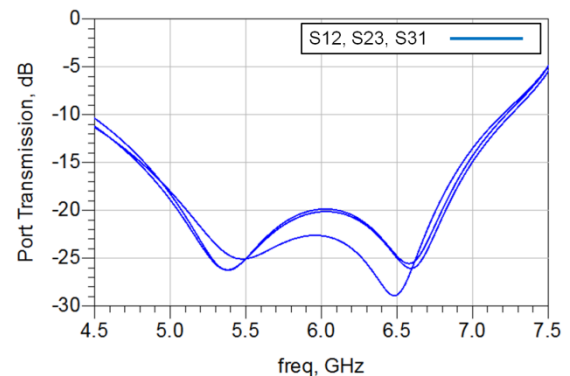


Fig.8. Transmission parameters of the forbidden paths.

VI. CONCLUSIONS

A novel active circulator topology was introduced, based on the integration of three active elements. Proposed structure exploits the quasi-circulating properties of three directive distributed amplifiers to achieve good isolation and insertion loss on a wide operating bandwidth. In order to demonstrate the effectiveness of the proposed topology a compact monolithic test vehicle was designed and simulated. Designed MMIC shows an insertion loss of 1.5 dB and an isolation of 15 dB on a 40 % bandwidth around 6GHz, featuring an area occupation of about 9 mm².



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