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A GaAs MMIC Phase Shifter Based on Coupled Spiral Inductors

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Abstract- **In this paper a GaAs MMIC phase shifter, based on a lumped quadrature hybrid, is described. The MMIC makes use of two interleaved spiral inductors in a transformer-like configuration to implement the quadrature coupler function. Two L-C resonant networks connected as load, provide the desired analog phase swing, under electronic control thus resulting a phase-shift capability of nearly 180°.**

I. INTRODUCTION

The growing interest in the personal communication (PC) field has stimulated the research of even more compact and integrated multifunction components. Although the PC applications span from the VHF to the millimeterwave frequency, the most broadly diffused applications actually are in the low-microwave band, e.g. the ISM band 2.45 GHz and 5.8 GHz. In order to achieve compactness and consequently a high integration of electronic functions, a monolithic implementation is highly desirable.

In complex transceiver structures [1], the RF section is composed of circuits whose realization is normally possible using components and subcircuits designed adopting a standard distributed elements approach. This is the case, for example, of amplifiers, mixers, modulators and phase shifter that made large use of power combiner, filters, matching network and directional coupler, which are normally designed on a distributed elements basis. The monolithic implementation of such asystem often results in large die area, owing to the dimension of the transmission lines, for that reason it is useful to consider new circuit configurations based on a lumped-element approach, [2].

This paper presents an analog phase shifter, based on a new 90 degree lumped element directional couplers (LEDC) topology. The LEDC circuit is based on a coupled spiral inductors pair and results particularly suitable for MMIC implementations [3].

Sample prototypes have been designed and tested using GEC Marconi F20 process. An analytical investigation of the new configuration is reported, along with experimental results.

II. PHASE SHIFTER DESIGN

A conventional scheme for the realization of a phase shifter is represented in Fig. 1. It consists of a forward coupled directional coupler and two varactor diodes. These latter components are connected to the direct and coupled port of the hybrid and are responsible for the IN-OUT phase shifting once a reverse bias voltage has been applied. Ideally the insertion loss is zero, however, due to the mismatch of the real structure and the low Q of the voltage controlled capacitor, a bias dependent input/output mismatch and an insertion loss is expected.

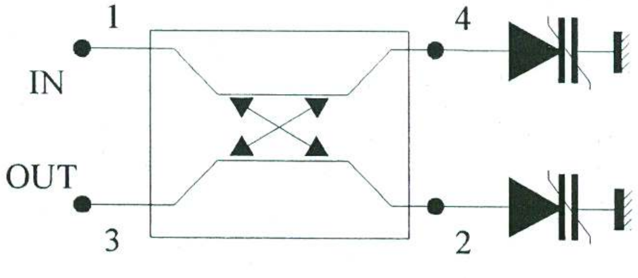


Fig. 1. Phase shifter diagram

The design of the phase shifter is based on an ideal 3dB directional coupler described in terms of S parameters by the symmetrical S matrix shows in (1).

$$S = \frac{e^{j\alpha}}{\sqrt{2}} \begin{bmatrix} 0 & 1 & 0 & j \\ 1 & 0 & j & 0 \\ 0 & j & 0 & 1 \\ j & 0 & 1 & 0 \end{bmatrix} \tag{1}$$

Following the general concept of implementing the directional coupling function, defined by the S-matrix in (1), by means lumped element only, the first step consist in a proper guess of the circuit topology. From the analogy between the TEM directional coupler and two coupled π-LC cells, [4], it is possible to implement the electronic function by the circuit in fig. 2, [3].

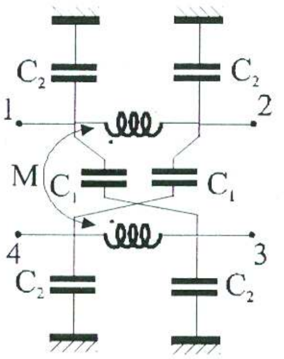


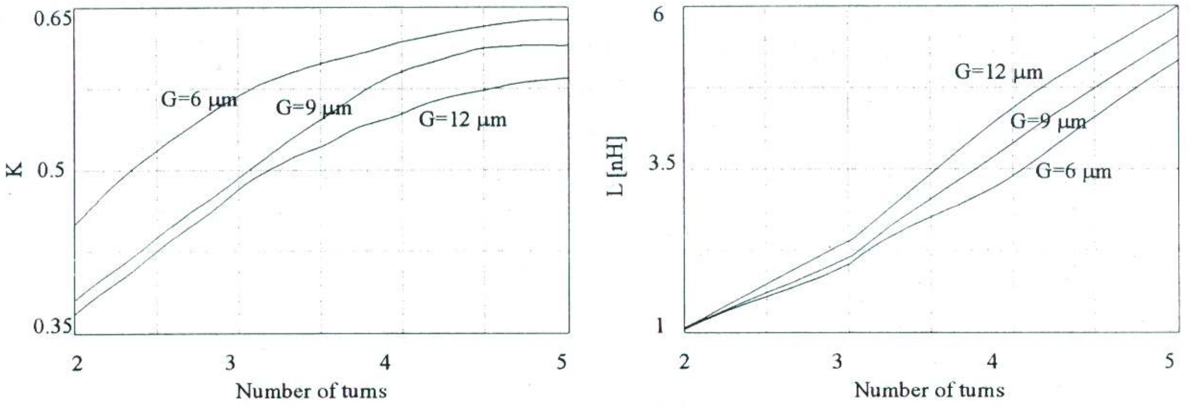
Fig.2. The proposed lumped element coupler topology

Relating the single components of the model to the symbolical Y matrix obtained from (1), the value of each components are defined in closed form, according to [5]. The LEDC design formulae are expressed as a function of the α parameter of equation (1) by the relations:

$$C_1 = -\frac{1}{\omega Z_o}\left[\frac{1-\sqrt{2}cos(\alpha)}{cos(2\alpha)}\right] \qquad C_2 = \frac{1}{\omega Z_o}\left[\frac{cos(\alpha+\pi/4)-1}{sin(\alpha+\pi/4)}\right]$$

$$K = -cot(\alpha) \qquad L = -\frac{1}{\omega}\frac{Z_o sin(\alpha)}{\sqrt{2}} \tag{2}$$

where K represents the ratio between the mutual inductance and the auto-inducance, M/L, associated to the coupled spiral inductors. The K factor varies from 0 to 1 and α varies from 3/2π to 7/4π. Assuming Z_0 equal to 50 Ω, the design is based on a right choice of α which in turn univocally determines L and M. Defined the operation frequency $\omega/2\pi$ and the system impedance, Z_0, the value of L and K are directly obtained from (2). The implementation of the coupled inductor is then possible in terms of number of turns and the conductor spacing determined by using the results of electromagnetic simulations based modelling. In the case of two concentric spiral inductors, the graphs in Fig.3, shows the K and L parameters as a function of the number of turns and the conductors gap, maintaining constant to 6 μm, the conductors width. This procedure allows to optimize with standard CAD tools the choice of the α parameter and, thus, circuit performances. The capacitances, defined by (2), are obtained laying out MIM capacitors in parallel to the parasitic capacitors associated to the spiral inductors pair.



a)

b)

Fig. 3. Concentric spiral inductors: parameters K (a) and L (a) as a function of the number of turns and conductors spacing: G=6/9/12 μm, conductor width=6 μm, inner dimension=40μm.

The schematic diagram of the phase shifter is represented in figure 1, where the directional coupler has been implemented by the LEDC previously described. The port 2 and 4 are terminating by series-resonant loads, whose resonance frequency can be electronically controlled by varying the load capacity. It is possible to show that the transmission coefficient between ports 1 and 2 is related to the reflection coefficient Γ(V), of the loads, by the following relation:

$$S_{21} = e^{j\left[\pi/2 + \angle\Gamma(v)\right]} \tag{3}$$

Equation (3) clearly denotes that varying the termination-load resonance frequency and, consequently, the phase of the reflection coefficient Γ(V), a corresponding variation of the transmission coefficient phase is obtained. The series resonant loads are implemented placing in series a proper inductors and a reverse biased source-drain shorted MESFET.

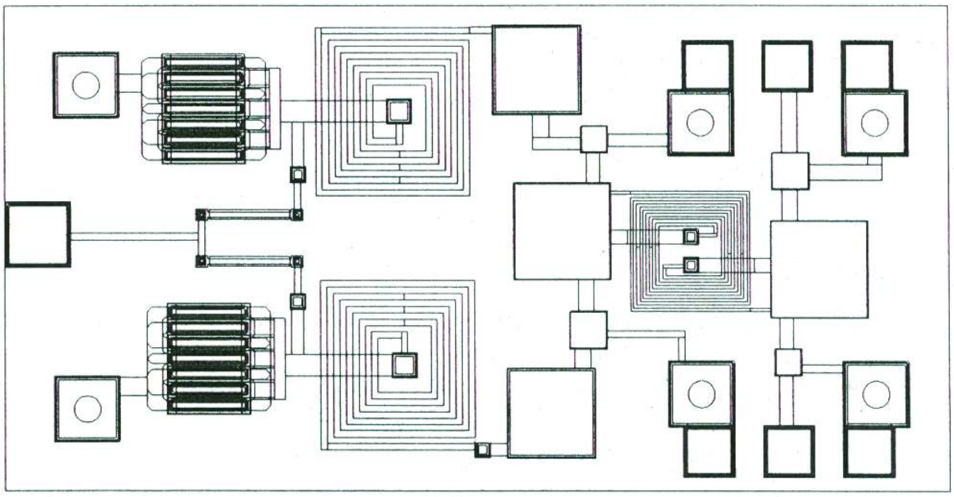


Fig. 3. Phase shifter prototype based on a lumped element direction coupler

III. PHASE SHIFTER REALIZATION AND RESULTS

A phase-shifter prototype, working at the 2.45 GHz has been implemented on a GaAs substrate by using the GEC-Marconi F20 Process. The lay-out is represented in Figure 3. MIM capacitors have been used to compensate for the parasitic capacitance between the two concentric spiral inductors. The values of the LEDC circuit element have been evaluated using the methodology described above, while the LC series has been designed in order to ensure the maximum phase span at the center frequency. The experiments are shown in Figure 4, where the phase and amplitude of the transmission coefficient, S_{21}, as a function of voltage are reported. A phase variation in excess of 180° is achieved, while a maximum of 11 dB in insertion has been observed.

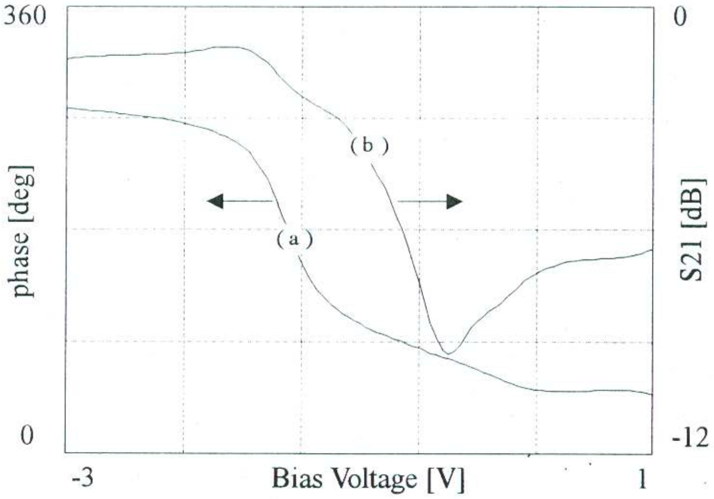


Fig. 4. In-Out response of the phase shifter prototype: phase (a) and amplitude (b) of the transmission coefficient.

IV. CONCLUSION

A compact analog phase shifter for ISM application, which is based on coupled concentric spiral inductors, has been described. The prototype working in the 2.45 GHz band has been realized using the F20 GEC-Marconi process. The experimental results shows phase swing capability in excess of 180°. A degradation in the insertion loss has been observed, this is mainly due to high series resistance associated to the voltage controlled capacitor which led to an high loss L-C resonant load. Work is ongoing to extend the operative frequency and to reduce the insertion loss adopting Schottky varactor diodes instead off source-drain shorted MESFET.

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