NEW BROADBAND BALUN STRUCTURES FOR MONOLITHIC MICROWAVE INTEGRATED CIRCUITS

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ABSTRACT

Two new passive balun structures, are described for use in MMICs. They are especially relevant to wideband push-pull power amplifiers, being capable of handling several watts of power. They operate over bandwidths of up to 3:1 and can provide large impedance level transformations. Exact network synthesis procedures are used to generate prototypes and a 3 dimensional field simulator is used to verify the corresponding physical circuits. A family of designs for 6-18 GHz and 6.5-13.5 GHz bands has been established.

INTRODUCTION

The two new types of passive balun to be described are intended primarily for use in microwave monolithic integrated circuits (MMICs) on GaAs and offer important performance advantages over alternative active designs. One of the most important advantages is that of power handling capability. They are able to handle several watts of RF power and can therefore perform as power combiners in push-pull power amplifiers. Their operating frequency bandwidth can be in excess of an octave anywhere in the frequency range 1-20 GHz. Another useful feature is their ability to incorporate impedance transformations between input and output terminals.

Equivalent circuits of the two new balun structures are given in Figures 1 & 2. With the exception of a lumped resistor, the first of the two is a purely distributed structure and is most suited to operating over bandwidths of more than 100% (Figure 1). The second is a mixed lumped/distributed structure, more suited to operating bandwidths of an octave or less but also more suited to providing large impedance transformation ratios (Figure 2). Because of the use of lumped elements, it is generally smaller than the first of the two types of balun but as a result of extensive folding of the transmission line elements, both structures are highly compact.

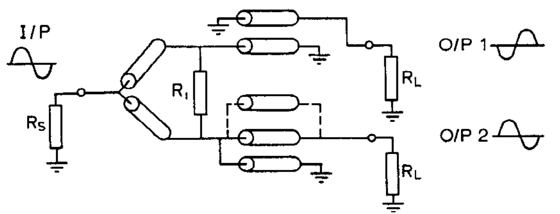

Figure 1. The transmission line configuration for the highpass balun

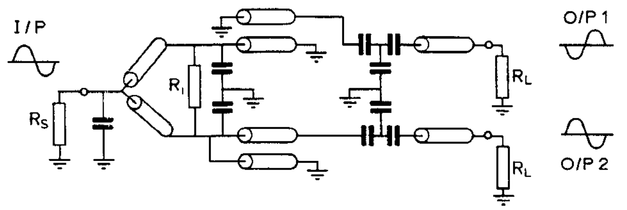

Figure 2. Basic lumped/distributed equivalent circuit of the compact bandpass balun

Exact network synthesis procedures are used in the design of the two baluns. Each balun comprises a pair of bandpass (BP) filters connected in parallel at a suitable point close to the input port. In the case of the first type, the bandpass filter relates to a prototype with a highpass (HP) frequency response. In the case of the second, the bandpass filter relates to a prototype with another bandpass response. For this reason they are referred to as the HP and BP types. In both types, 180 degrees of phase shift is achieved by splitting a signal into two identical samples and inverting one of the samples. For this purpose, the baluns contain two coupled line sections as illustrated in Figures 1 & 2, one which is present in the non-inverting arm of the balun and the other present in the inverting arm. These two sections have identical transmission line equivalent circuits except that in the case of the first section there is an additional ideal transformer with a turns ratio of -1:1. Resistor R_i is a balancing resistor which dissipates any odd mode power and ensures a good match at the two output arms.

A HP BALUN FOR 6-18 GHz

It is possible to design the HP balun for various instantaneous frequency bandwidths but it is particularly suited to bandwidths between 2:1 and 4:1. A 6-18 GHz balun has been designed and constructed and this will be used as a design example. Synthesis of the relevant filter produces an S plane prototype of degree 3 and of the form shown in Figure 3.

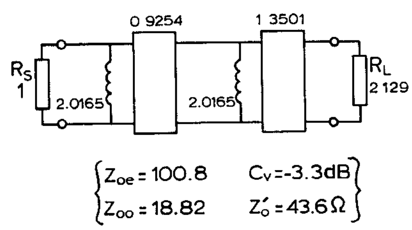

Figure 3. Highpass S plane prototype for 6-18 GHz balun

Commensurate frequency (f_s) was 12 GHz and the passband insertion loss ripple (T_p) was 0.1 dB. This bandwidth and ripple value conveniently give the required 2:1 terminal impedance ratio, which, when two such filters are connected in parallel at the common input terminal, give a balun with equal port impedances. However, other terminal impedances can be produced by making changes to the bandwidth, the passband ripple or by moving inductance through the network using suitable transforms (e.g. Kuroda transforms[(1)]).

The unit element plus the pair of surrounding inductors, correspond to the coupled line sections in the real balun. For the inverting section with short circuits on alternate ends of the two lines, the distributed capacitances C_a, C_b and C_{ab} are given by a/L_1, a/L_2 and a/Z_0 respectively. C_a and C_b are the capacitances of the strips, C_{ab} is the inter-strip capacitance, L_1 and L_2 are the prototype inductor values whilst Z_0 is the value of the unit element. The constant a is $377/\epsilon_{eff}$ where ϵ_{eff} is the effective dielectric constant of the microstrip section. For the non-inverting coupled line section with a short circuit on only one end of one of the lines, C_a, C_b and C_{ab} are given by a/Z_0, a/L_1 and a/L_2 respectively. However, as indicated in Figure 1, an additional transmission line may be wired in parallel with the section to allow the coupled lines to be of equal width, in which case, the relevant value of Z_0 rises to the value of L_1.

For symmetrical couplers, odd and even mode impedances are given by:

$$Z_{oe} = a/C_a \ \Omega$$

and

$$Z_{oo} = a/(C_a + 2C_{ab}) \ \Omega.$$

They are related to the voltage coupling ratio C_v and an impedance Z_o' by:

$$C_v = 20\log_{10}((Z_{oe}-Z_{oo})/(Z_{oe}+Z_{oo})) \text{ dB}$$

and

$$Z_o' = \sqrt{(Z_{oo} \times Z_{oe})} \ \Omega.$$

Figure 3, gives values of these parameters for the inverting coupler of the balun, the -3.3 dB coupling ratio requiring the realisation of the coupler as a 4-finger interdigitated structure. Coupling ratio for the non-inverting coupler is a much more modest -6 dB which can be realised with a conventional pair of edge-coupled lines.

An analytic derivation of the value of the balancing resistor R_i, is a problem of considerable complexity, beyond the scope of this paper. However, in practice its derivation is trivial by computer adjustment of its value to optimise output port reflection coefficient (R_i = 88 ohm).

The 6-18 GHz baluns have been fabricated on 2" wafers of GaAs at the PHILIPS MICROWAVE MMIC foundry in Limeil, France. A photograph of one of the balun chips after fabrication is shown in Figure 4. To minimise the area occupied by the balun and also to make use of a single via hole for all the ground connections, the line elements including the couplers have been folded. Clearly the aspect ratio of the balun can be adjusted to suit any specific application. Here, the balun has been made short and wide to enable it to be positioned as the final power combining element at the end of a power amplifier chip. Its overall size is approximately 0.7 x 2.0 mm. Substrate thickness is 0.1 mm.

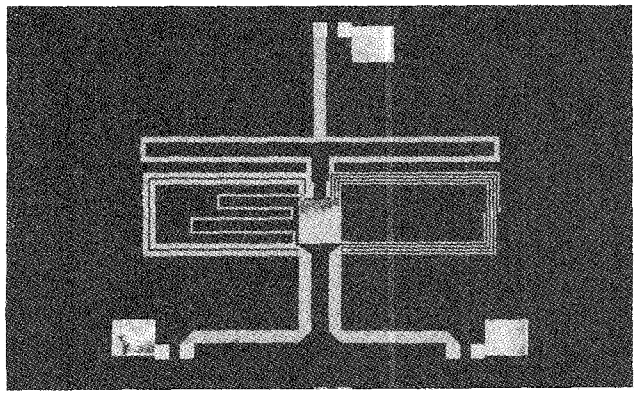

Figure 4. 6-18 GHz MMIC balun (0.7 x 2.0 mm)

Predicted frequency responses of the 6-18 GHz balun are presented in Figure 5. These were calculated directly from an equivalent circuit of the form given in Figure 1 which contains ideal transmission line elements. Phase responses of S_{21} normalised to a reference line, are plotted in the upper half of the diagram and as expected, phase difference between the responses is 180 degrees at all frequencies inside and outside the passband. The plot of S_{21} magnitude is in respect of each of the two output ports and shows there is a constant, 3 dB power split between the two ports over the whole 6-18 GHz band.

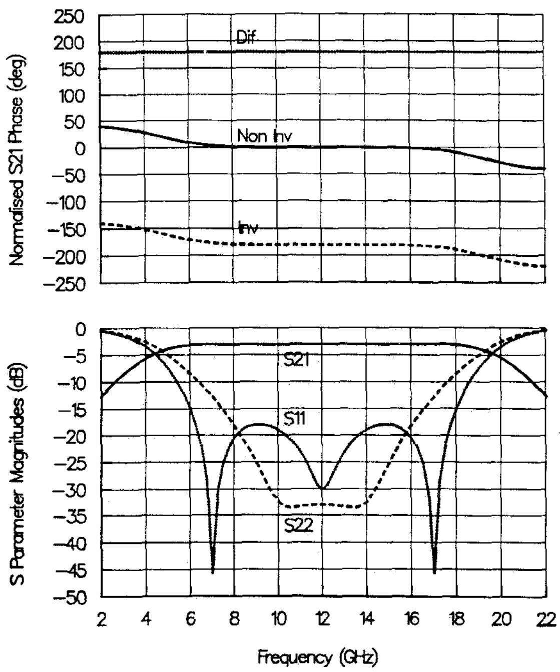

Figure 5. Predicted frequency responses of 6-18 GHz balun

Measured performance of the balun is illustrated in Figure 6. Amplitude responses of the two arms are smooth and track each other to within ± 1 dB over the whole 6-18 GHz band. Excess loss is of the order of 1 dB. The phase responses in Figure 6 indicate that there is an effective path length difference between the two arms. This is due to inaccuracies in the geometrical modelling of the structure and is not a fundamental characteristic of the design.

When the path length difference is corrected by adding a short length of line on the non-inverting arm, the absolute phase difference is 180 ± 4 degrees over 6-18 GHz.

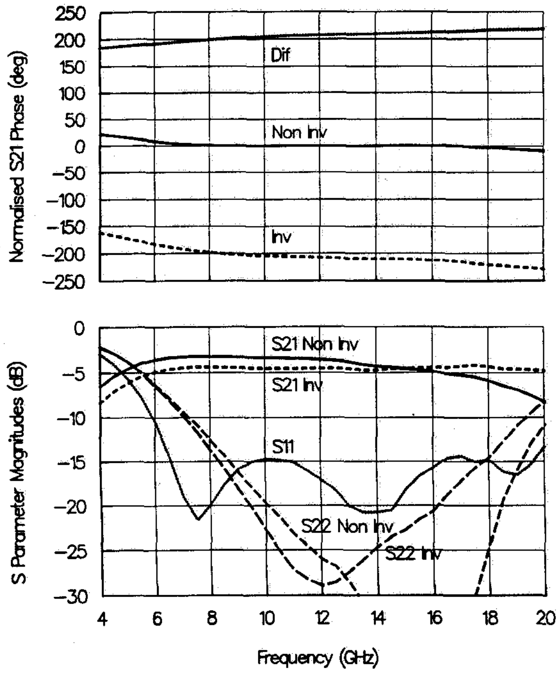

Figure 6. Measured frequency responses of 6-18 GHz balun

Since the fabrication of the 6-18 GHz balun, a powerful circuit simulator has become available within the PHILIPS organisation which performs a full 3 dimensional field analysis. The program, called FACET[2], is a CAD package developed at Philips Research Laboratories for simulation of the RF behaviour of printed circuits with arbitrary geometry. FACET derives a lumped equivalent model of the network which accounts for all capacitive and inductive couplings and dielectric and ohmic loss. Both the topology of this network and its component values are automatically derived from the layout geometry and physical properties of the materials. Integral methods and pre-computed basis functions combine to give numerically efficient solutions for the component values. A network model describing both printed and other components is automatically loaded into a conventional circuit analysis package which can run either a time or frequency domain simulation.

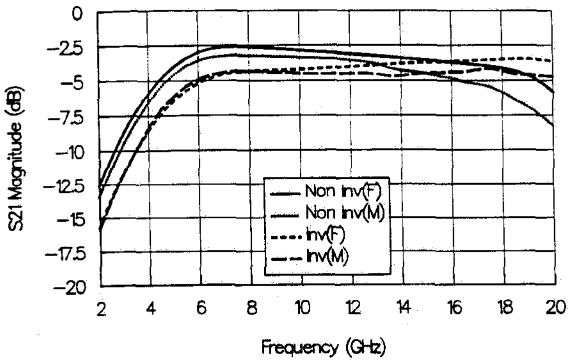

Figure 7. Measurement v FACET Simulation, 6-18 GHz balun

FACET has been used to simulate the performance of the 6-18 GHz balun. Evidence of the excellent agreement between the FACET simulation and the measured performance is presented in the plots of S_{21} against frequency in Figure 7. Agreement between measured and simulated S_{21} phase responses is also close (± 4 degrees), enhancing the prospect of using FACET to correct the path length differences in future versions of the balun.

BP BALUNS FOR 6.5-13.5 GHz

Despite the capability of the HP balun to deliver ultra wideband performance in an MMIC, a reduction in size would be an advantage. If instead of a HP S plane prototype, the balun is based on a BP prototype, several new opportunities for substantial size reduction are to be found. The length of the lines becomes an additional degree of freedom in the design and can be chosen to be as little as a tenth of a wavelength in the region of the passband. Furthermore, the lengths of the elements no longer have to be identical to preserve correct behaviour in the passband and lengths can be traded against impedances to the extent that some elements become treated as pure lumped elements. In addition to size reduction, the BP prototype allows a considerable range of impedance transformation to be incorporated into the balun, adjustment of which can be achieved by simply altering the symmetry in the T arrangement of capacitors near the output ports (Figure 2).

A set of MMIC baluns based on BP prototypes have been designed for the 6.5-13.5 GHz frequency range, offering impedance ratios of 50:50, 50:25 and 50:12.5 ohms respectively. All are derived from the same basic S plane prototype, the different port impedances being achieved by transforming series capacitance towards or away from the output load. At the outset, band-edge and commensurate frequencies were specified to be 6.66 GHz, 13.33 GHz and 30 GHz respectively, with passband ripple set to 0.1 dB. After exact synthesis of the prototype, transformations are applied to achieve the required impedance ratios together with realisable impedance levels for the various circuit elements. It is during this process that line lengths are modified and open circuit stubs are converted into lumped capacitors. Choosing an octave instead of a 3:1 frequency bandwidth, allows both the inverting and non-inverting coupled sections of the baluns to be simple edge-coupled lines. The non-inverting coupler, however, is not symmetrical.

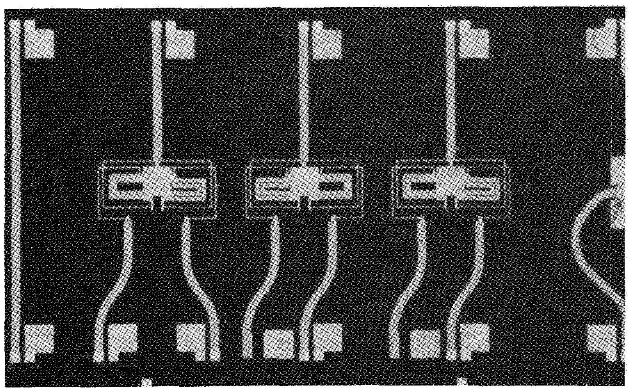

Figure 8. Folded 6.5-13.5 GHz bandpass MMIC baluns (0.55 x 1.1 mm)

A photograph of an MMIC cell of three of the 50:50 versions of the BP balun is shown in Figure 8. Two of the set of three have alternate output ports terminated on-chip by 50 ohm loads to enable 2-port RF wafer probing. In terms of layout, these baluns are broadly similar to the HP balun, the coupled line sections being folded into U sections so that a single via in the centre can provide all the necessary ground connections, including those required by the shunt capacitors. Overall size of each balun element is 0.55 x 1.1 mm, which is nearly half that of the HP balun.

This first set of BP baluns were designed and fabricated before the FACET simulator was available. In view of the highly compact nature of their layout, it was not surprising to find that the effects of parasitics were more pronounced than for the HP balun. RF measurements showed the effects of the parasitics to be unacceptable and consequently, an investigation was undertaken using FACET, aimed at their identification and elimination.

Despite the close proximity of the microstrip elements, capacitive cross-coupling was not found to be a significant factor. One of the two major causes of the problems was the extensive folding of the coupled line sections. Experiments showed that even a single, 45 degree bend in the coupled lines caused distortion of the frequency responses and the presence of two, 90 degree bends could, in the absence of any other circuit parasitics, destroy the balun performance. The other major problem was associated with the vias. At 240 x 240 μm, their size is a significant proportion of the length of the coupled lines, such that the effective length of the lines with respect to the real ground connection is unclear. Furthermore, the connection of shunt capacitors to ground at the same vias used for grounding the coupled lines, was corrupting the basic circuit configuration. The via, as a common ground path, was acting as an undesirable feedback element. It was, therefore, necessary to take proper account of the via inductance in determining the dimensions of the coupled lines and also to ensure that the shunt capacitors were grounded by their own vias.

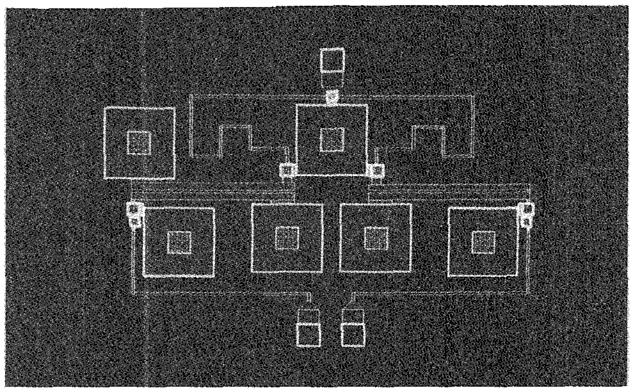

Figure 9. Final layout, unfolded 6.5-13.5 GHz bandpass balun (0.7 x 1.5 mm)

The layout of one of a revised set of BP baluns is shown in Figure 9. This particular balun is a 50:25 ohm version. There are now six vias instead of the previous total of one, the coupled lines are straight and the shunt capacitors use separate vias from those of the coupled lines. Despite the changes, the circuit still measures only 0.7 x 1.5 mm which is a little bigger than the original design but still much smaller than the HP balun. It also embodies the impedance transformation that was not realisable in the HP balun. A complete FACET analysis of the new layout has been performed, the results of which are presented in Figure 10. The difference between the normalised phase responses is 184 ± 4 degrees over the 6.5-13.5 GHz passband. The S_{21} amplitude responses of the output ports track each other to within ± 0.5 dB whilst excess loss is about 1 dB. Port reflection coefficients are shown rising to -10 dB in the centre of the passband. This is due to the residual effects of the grounding of circuit elements by large vias. Port reflection coefficients and circuit performance in general could be improved by reducing the size of the vias. Given the proven accuracy of FACET in analysing the behaviour of previous baluns, confidence is high that the measured performance of the revised BP baluns will be satisfactory.

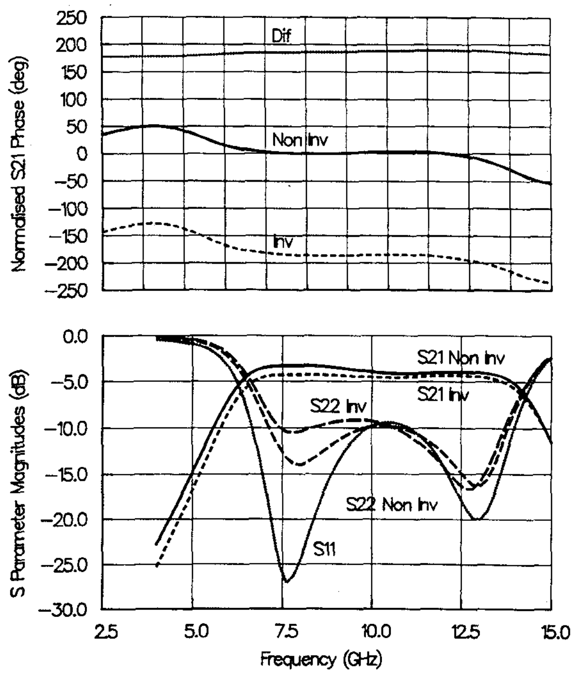

Figure 10. FACET simulation of 6.5-13.5 GHz balun

CONCLUSIONS

Two new passive balun structures have been described. They are sufficiently compact to be used to considerable effect in GaAs MMICs, particularly where wide bandwidths and high powers are involved. Practical designs for 6-18 GHz and 6.5-13.5 GHz operation have been described. The designs were verified by a 3 dimensional field analysis of their geometrical structures. Suitable applications include phase shifters, mixers and power amplifiers.

REFERENCES

(1) Kuroda Identities to be found in: Ozaki, H. and Ishii, J., "Synthesis of a Class of Stripline filters," IRE Transactions on Circuit Theory, vol. CT-5, June 1958.

(2) Milsom, R.F., "FACET - a CAE System for RF analogue simulation including layout," 26th ACM/IEEE Design Automation Conference, pp622-625, 1989.