Reinventing the Balanced Amplifier

Steve C Cripps

Cardiff University, UK.

Introduction; the Classical Balanced Amplifier.

The quadrature balanced amplifier was, for some decades, the default configuration for implementing broadband amplifiers in the GHz frequency range (Fig.1). Its key property was the ability to make cascadable gain modules despite considerable, and intentional, internal mismatch of the active transistors over octave or multi-octave bandwidths. In an era when the available gain from an individual transistor above 10GHz was well below 10dB , useful amplifiers required the cascading of several stages and the balanced configuration made this relatively easy, taking account specification requirements on gain flatness and stability. The original invention of the balanced amplifier is usually attributed to Kurakawa in a 195? Paper [1], however the widespread deployment of the configuration had to wait until a practical planar interdigital 3dB quadrature coupler was developed, in a 1969 paper by Lange [2]. Thus the balanced hybrid module, illustrated in Fig.1(b), became the mainstay of a burgeoning microwave amplifier industry, which was focused on the replacement of short lifetime Travelling Wave Tube (TWT) amplifiers in military systems.

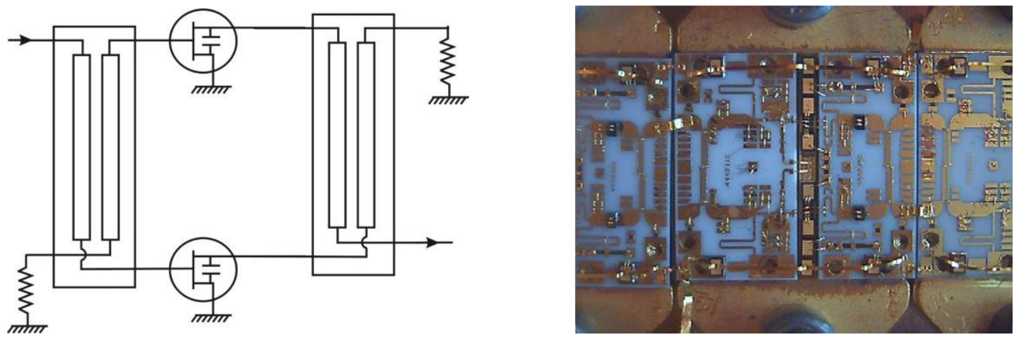


Fig.1.   (a) Balanced amplifier configuration, (b) Practical implementation using Lange couplers.

The advantages of the balanced configuration can be summarized as follows:

(a) Broad bandwidth; even despite the roll-off of coupling factor in single section 3dB couplers, flat frequency response can be maintained up to a 4:1 bandwidth,
(b) Power enhancement; the power of the two individual stages is combined at the output, thus giving a broader band match than an equivalent single-ended approach,
(c) Improved stability, allowing the use of devices having k factor substantially less than unity
(d) “Soft failure” properties.

Despite its obvious advantages, the balanced amplifier did not fare so well in the wireless communication revolution of the “00’s”. These new applications used very narrow bandwidth allocations so that transistors could easily be matched over the required bandwidth, and the low GHz frequencies, along with some major technology improvements, allowed for much higher individual stage gains. The move to integrated RFIC technology also posed problems for realizing the 3dB couplers, whose quarter-wave dimension proved hard to work with. As such, the balanced amplifier had a widespread decline in use.

The "Unrealized" Properties; Load Mismatch and the LMBA

Curiously, despite its widespread use for several decades, the balanced amplifier had some additional interesting properties that went largely unnoticed during its heyday.

The first of these concerns the very likely situation where the amplifier is presented with an output termination that is significantly mismatched from 50 Ohms. As shown in Fig.2, the output mismatch is not directly transmitted to the individual balanced stage output ports but the output load reflection magnitude appears at a 180 degree offset on each side. As such the gain and power of one side may show less performance degradation compared to the other. This is a particularly valuable asset in power amplifiers and largely eliminates the need for an output isolator which has become almost statutory in single-ended PA designs.

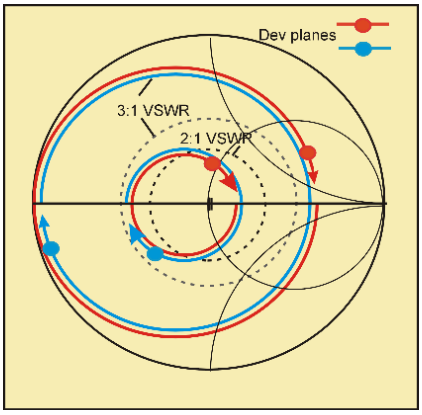


Fig.2. Balanced amplifier, device plane impedances with mismatched output termination.

Secondly, the balanced amplifier can be rewired to allow for the impedance presented at the individual balanced stage output ports to be controlled using an external RF source. This configuration, known as a Load Modulated Power Amplifier, or LMBA, was originally patented as a theoretical concept by Dent [3] but more recently practically implemented at GHz frequencies by the UK Cardiff CHFE group [4].

The Load Modulated Balanced Amplifer (LMBA)

Fig.3(a) shows the basic configuration for an LMBA. A "Control Signal Power", or CSP, that is frequency and phase synchronized is applied to the output coupler port that in a conventional balanced amplifier would be terminated with a matched load.

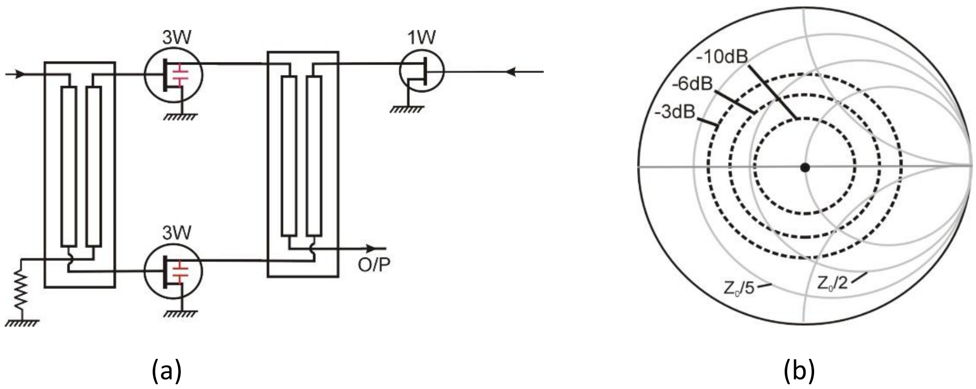


Fig. 3. (a) Load Modulated Balanced Amplifier, (b) effect of control power on device plane impedances.

It is a fairly straightforward piece of theory to show that for the ideal situation of a symmetrical 3dB lossless coupler, the output impedance presented to each balance device are given by the expressions

$$Z_2 = Z_0(1 - \frac{\sqrt{2} I_{\mathrm{mod}}}{I_{bal}})$$

$$Z_4 = Z_0(1 - \frac{\sqrt{2} I_{\mathrm{mod}}}{I_{bal}})$$

where the device plane impedances are Z2, Z4, the device output currents have an equal amplitude I_{bal}, and the CSP injected current I_{mod}. This leads to the more pragmatic result shown in Fig.3(b), which shows the range of impedance modulation that can be obtained at various relative levels of CSP, given a full phase sweep of the CSP signal. Two, possibly counter-intuitive, results emerge from this analysis [4]:

(a) The modulated load presented to each balanced device is the same,
(b) The power inserted at the CSP port is fully recovered at the main amplifier output , regardless of its phase setting.

The most obvious application for the LMBA is the active retuning of the output match of an RF power amplifier (RFPA) in order to maintain high efficiency under power back-off (PBO). As such it may be compared with the more established approach to this problem, the Doherty PA (DPA). In brief, the advantages of the LMBA over the DPA are:

(a) Wideband, multi-octave performance (limited mainly by the coupler),
(b) Lower relative auxiliary (CSP) power for a given load modulation
(c) Full recovery of CSP power at output.

There are some disadvantages,

(d) The CSP amplifier will not receive the advantageous load modulation seen in the auxiliary amplifier in a DPA.
(e) The lower CSP power requirement leads to some non-linearity in the LMBA response.

The bandwidth capability of the LMBA is certainly its leading selling point, as illustrated in the performance of a prototype built at Cardiff (Fig. 4, [4]).

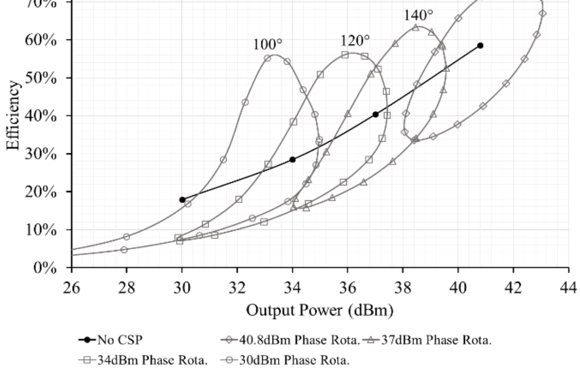


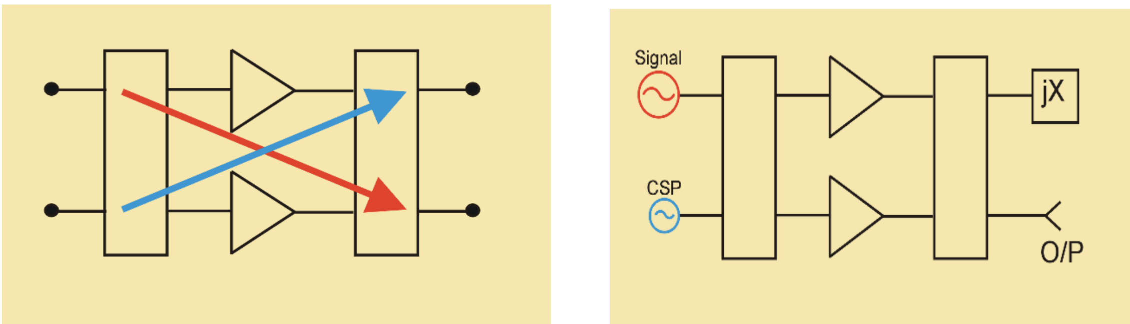
Fig.4. LMBA prototype, showing range of active tuning.

LMBA Variations

(i) Single input LMBA: Initial work at Cardiff used an external signal generator and buffer amplifier to generate the CSP signal. In practical applications, the CSP signal can be derived directly from the input, [5].

(ii) Inverted LMBA: The linearity issue in (e) above can be resolved by using a so-called "inverted LMBA", [ref], in which the roles of the balanced and CSP amplifiers are reversed. This leads to a versatile broadband RFPA architecture which has excellent PBO efficiency over octave bandwidths [6].

(iii) The Orthogonal LMBA: The OLMBA is another variation which has some interesting and useful properties [7,8], and has become the main focus at Cardiff, The OLMBA uses the gain of the balanced stage to amplify both the main signal and the CSP, as shown in Fig.5.



(a) (b)

Fig.5 Evolution of the Orthogonal Load Modulated Balanced Amplifier (OLMBA);

(a) "2-way" balanced amplifier, (b) OLMBA with CSP on input side.

A conventional balanced amplifier can in fact be used as a dual amplifier, shown in Fig. 5(a), where two essentially independent signals can be amplified using two orthogonal paths into two independent outputs. LMBA action can then be obtained by reflecting one of the outputs back into the output coupler, using a reactive rather than a matched output port termination for the CSP path (Fig. 5b). The analysis of the OLMBA is rather more complicated [6,7] but the outcome is that the load modulation, although showing somewhat less range than in the LMBA, can now be obtained using essentially negligible CSP power input. Fig.6 shows measurements from a demonstrator broadband OLMBA which exhibits useful efficiency enhancement using a low level CSP input.

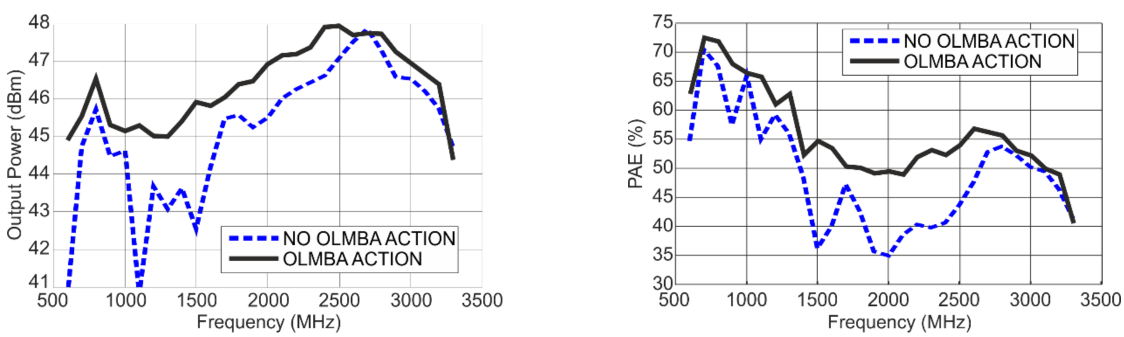


Fig.6. OLMBA demonstrator [7] showing 6:1 bandwidth enhanced performance using a CSP level of -10dB relative to the main signal, and a 4-way switched jX port.

Mitigation of output port mismatch using the OLMBA.

The regular balanced amplifier has already been noted as being less sensitive to output port mismatch than an equivalent single-ended design. By adding the two key features of an OLMBA configuration; an input control signal having a power level substantially lower than the main signal input, and a variable reactive termination on the isolated output coupler port, it has been demonstrated that an output mismatch of up to 3:1 VSWR can be substantially mitigated over a wide amplifier bandwidth [ref]. The underlying theory becomes quite complicated; there are now three independent CSP settings, (a) the relative (CSP/signal) power, (b) the relative CSP phase, (c) the phase of the reactive "jX" termination. The device plane impedances thus become quite complicated functions of these independent variables [ref] but do show some special cases that are indicative of the capability of the OLMBA to mitigate the effects of a termination mismatch. For example, analysis shows that by suitable selection of the three CSP parameters it is always possible to transform the two device plane impedances to a single value on the real axis, regardless of the phase of the output mismatch, as indicated in Fig.7.

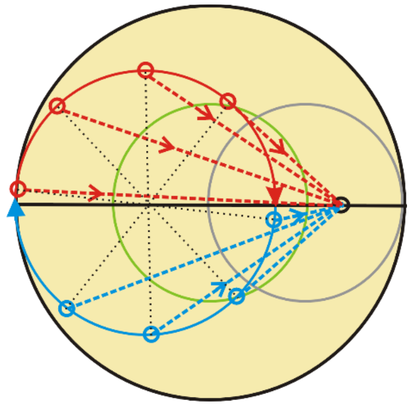


Fig.7. OLMBA transforms device plane impedances to single point on real axis under 3:1 VSWR termination.

In general, the optimum case for each individual VSWR magnitude and phase has to be determined experimentally. Fig 8 shows a summary of the OLMBA mitigation action for a demonstrator built using a pair of Wolfspeed 25W devices. This shows the result of performing a loadpull measurement in order to determine the range of output termination mismatch which can still deliver a target specification of 45% efficiency and 45dBm power. The OLMBA is directly compared with a balanced amplifier having an otherwise identical circuit design.

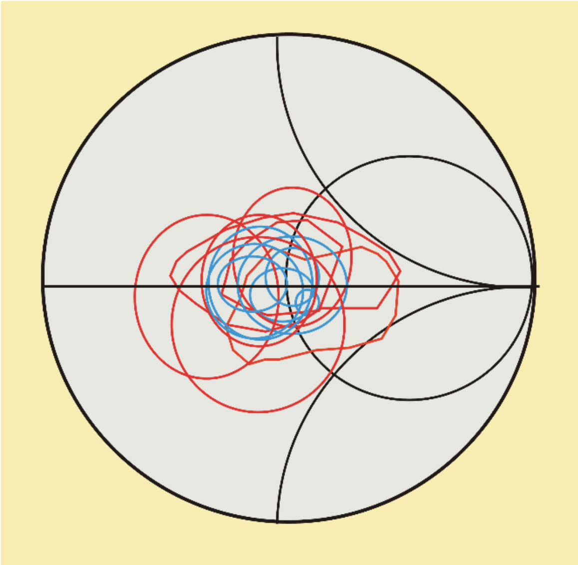


Fig.8 Direct comparison of termination sensitivity, OLMBA (red), balanced (blue). Contours show areas where a target specification (45% PAE, 45dBm) is met.

Conclusions

The quadrature balanced amplifier still offers a range of useful properties to the RF amplifier and system designer. Recent evolutionary techniques such as the Load Modulated Balanced Amplifier (LMBA) and Orthogonal Load Modulated Balanced Amplifier (OLMBA) have been proposed and demonstrated as having highly useful properties which address modern microwave systems, both in military and mobile telecom applications.

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