An Analysis of Parkervision Patent 7,184,723 (and some associated claims)

Background

My name is Dr. Steve Cripps. I have been asked to render an expert opinion on an issued patent by Parkervision relating to RF power amplifiers, and on a number of related patent applications, also by Parkervision.

I have worked in the field of RF power amplifiers for 25 years. I am the author of 3 books on the subject of power amplifiers: "**RF Power Amplifiers for Wireless Communications, Second Edition" (2006), "Advanced Techniques in RF Power Amplifier Design" (2002), and "RF Power Amplifiers for Wireless Communications" (1999),** all published by Artech House**.** I have published several papers and am a regular contributor to technical workshops in the RFPA field. I have consulted for at least 15 companies on power amplifiers, including many leaders in the field of PA design. I have a Ph. D and masters degree from Cambidge University, England (1974). I am the current chair-elect of the Power Amplifier subcommittee of the Institute of Electrical and Electronic Engineers, Microwave Theory and Techniques Society (IEEE-MTT) , and regularly participate in the review of papers submitted to the International Microwave Symposium and the Transactions of MTT. I have no personal financial interest, direct or indirect, positive or negative, in Parkervision. I have never visited the Parkervision facility and am not acquainted with any of the patent authors. I am also not aware of any peer-reviewed publications in the RF Power Amplifier field by any of the authors.

Introduction to RF Power Amplifiers (RFPAs)

Some background first. A typical radio communications signal consists of a radio-frequency "carrier" which is "modulated" by varying its instantaneous amplitude and timing (or "phasing"). The modulation is what contains the information, or "intelligence" being transmitted. Such signals can be generated, along with all of the necessary coding and system management content, very easily using modern digital integrated circuits. Unfortunately, the power level at which these signals can be readily generated is too low for a typical mobile communications system, where the mobile transmitter (e.g. a cellular mobile phone) has to generate a signal that is strong enough to be detectable by a "base station" several miles (or even 20-30 miles in rural areas) away. So it is necessary to take the signal and amplify it, usually to a maximum level of 1 Watt or thereabouts for a mobile, and with average power levels of approximately 50-100 mW , using a radio frequency power amplifier ("RFPA"). This process consumes a large amount of power. Even if the PA were 100% efficient, there would still be a drain of 1 Watt from the battery, which would run it down in a matter an hour or so. There is another problem, which is that the PA will to some extent distort the signal, which can cause bad reception at the other end of the link, and also breach on-air regulations. Unfortunately, it is a matter of well established fact that there is a trade-off between efficiency and distortion in PA design. PAs which do not meet the regulatory specifications can have quite high efficiency, and in assessing claims for improved PA design techniques and technology it is vital that efficiency numbers are quoted at comparable (and acceptable) distortion levels. ***It is not difficult to make a PA with much higher efficiency than that typically quoted in current commercial RF PA products, if the distortion specs are ignored.***

This linearity/efficiency trade-off is such a major issue in radio communications that sometimes system designers bypass it by using "constant envelope" modulation. This eliminates the amplitude variation as a means of conveying information, which is then carried entirely in the phase of the transmitted carrier. The European GSM system is an example of this. The problem with amplitude modulation (AM) is that at times the level of the signal is very low, so that at these times the PA is consuming much more power than is really necessary. An analogy would be the ownership of a double-decker bus as one's sole means of personal transportation. This would be just great for transporting 100 wedding guests on the very infrequent occasion that one of your relatives gets married, but highly wasteful of gasoline and parking space when using it every day to drive to work. A better solution would be to have another smaller vehicle to use for short personal trips. In the case of an RFPA, it is not so easy to "switch vehicles" during the time the signal transitions from high to low levels, due to the fact that the "switch" has to be enacted in a matter of nanoseconds, which even in electronic terms is quite fast. But over the last seventy years or so, many schemes have been proposed for RF PAs which in effect do just this; they switch between a high power device and a lower power device at appropriate times in the signal modulation cycle. The Doherty PA [1] is an example of this, dating from the 1930's and currently being widely deployed in cellular basestation transmitters.

The core of the PV patents and claims uses another well-known and widely researched technique for bypassing the linearity-efficiency tradeoff in systems which use AM. The basic idea is to note that constant-amplitude, or phase modulated (PM) signals are much less distorted by an RF PA and this enables the PA to run at much higher efficiency (again, this is demonstrated in the GSM system). This approach has been the subject of many papers over several decades, and is generically termed "Outphasing". For example an entire book devoted to outphasing techniques for RFPA applications was published in 2003 ([3], note that two of the co-authors, Larson and Asbeck, are professors at UC San Diego and recognized authorities and leaders in RFPA research, with dozens of peer-reviewed research papers and other publications in leading institutional journals and conferences over the last decade or so). In a classical and widely cited paper by Chireix [2], dating again from the 1930's, two PAs are run with constant amplitude, phase modulated signals, and their outputs are summed. The two PAs thus run very efficiently, and the AM signal can be generated at the summed output by suitable differential phasing of the two input signals.

Such a configuration is not, strictly speaking, a Power Amplifier (PA) as such, inasmuch as the input signals do not themselves replicate the required amplitude-modulated output signal (Chireix himself noted this distinction in the title of his paper [2]). The fact that an outphasing system is in effect a complete transmitter architecture, rather than a Power Amplifier (PA) is widely regarded as a hindrance in a commercial sense, in that a potential OEM user has to implement the additional support circuitry and signal processing which is required to synthesize the appropriately phase-modulated drive signals to each individual power transistor cell. Such circuitry is likely to consume more power than the simple driver amplifier used in a conventional PA chain. Notwithstanding this significant detraction, however, Chireix's technique represented an important breakthrough in the 1930's, due mainly to the use of a special kind of power combiner, which incorporated an impedance inverter. The PV patents, however, appear to focus entirely on the simple parallel addition of the separate constant amplitude, phase modulated signals. Indeed in the background section of patent 7,184,723 the following comments are made:

"……***existing outphasing techniques are deficient in satisfying complex signal amplification requirements, particularly as defined by wireless communication standards……"***

I would refer the reader to reference [6], where at the 2004 International Microwave Symposium Grundligh et. al. reported a full implementation of a high efficiency outphasing scheme, for the very challenging 802.11a signal environment at 5.1GHz. The application was fully integrated in the form of two packaged chips. The quoted efficiency, including RF driver stages, was 33%, which at the time was more than double the efficiency available from competing devices (but has since been equalled by other manufacturers using different approaches such as Polar modulation). It was, however, a complete transmitter, not a PA, and the efficiency did not include the power drawn by the silicon driver/processor chip. This chip in fact performed numerous additional functions to supplying the output transistors with suitably phase modulated signals, so the "real" efficiency remained debatable.

The PV patent (para. 5) continues,

"In one aspect, existing outphasing techniques employ an isolating and/or combining element when combining constant envelope constituents of a desired output signal. For example, it is commonly the case that a power combiner is used to combine the constituent signals. This combining approach, however, typically results in a degradation of the output signal power due to insertion loss and limited bandwidth and, correspondingly, a decrease in power efficiency".

I cannot agree with this paragraph. Firstly, the "combiner" in a Chireix outphasing configuration is only a combiner in the most generic sense, inasmuch as the output from two devices is being added. The actual function of the passive circuit elements in the so-called "Chireix combiner" is that of impedance inversion, which converts a saturating PA stage from a voltage source back to a current source. The losses can be made quite negligible (maybe less than 0.1dB). The impedance inverter is the key element which enables an outphasing amplifier to have higher efficiency than a conventional linear PA.

As shown in [6], the impedance inverting function can even be absorbed into the passive matching circuitry that will always be required to transform the low impedance of the RF power output transistors to the system level impedance. As far as the limitations in RF bandwidth are concerned, it should be noted that wireless communication band allocations are extremely narrow, and the bandpass response of any power combiner will usually be quite adequate to work effectively and with negligible insertion loss over the entire operating bandwidth. Outphasing systems are, in fact, very bandwidth limited, and this can be identified as a major obstacle in their commercial use in modern wireless communications. This limitation is however due to the frequency dependence of the outphasing process itself rather than the bandpass response of the combining, or inverting, elements.

I see no reference in the PV patent to the use of impedance inversion, the key breakthrough introduced by Chireix in his 1938 paper. There is also no reference or indication to the use of any form of load modulation, another key efficiency enhancement concept originally proposed by Doherty and currently undergoing extensive deployment in the wireless communications industry.

Patent 7,218,899

For several decades, it has been widely recognised in the RF PA industry that simple parallel connection of two amplified constant amplitude signals into a fixed common load resistor will not result in improved efficiency, in comparison to conventional linear amplification methods. **Yet this is precisely what PV appear to consider as their "revolutionary" technique in this patent**. Despite the extensive reference lists in their patents, PV appear, remarkably, to be uninformed on what is common knowledge in the RFPA industry. PV appear to promote, and claim as revolutionary, what in mainstream PA circles has been rejected as a useful approach, where a simple power combiner, or parallel output connection, of the two amplifying devices is used to sum the two output currents. The problem with this simplistic approach is that the two devices "talk" to each other, and the output of one seriously modulates the output (technically speaking, the output load impedance) of the other device. The result of this, which can be shown in very simple mathematical language (see Appendix) , is that the output voltage at each device now shows the very amplitude variations that the whole system was devised, from an efficiency viewpoint, to remove**.** So such a system, in the absence of a Chireix-style combiner, has much the same low efficiency as a conventional PA which amplifies the signal in its original, amplitude modulated form. Reference [3] gives a more detailed description of the basic outphasing concept (section 1.4, pp27-32), stressing its long history and reaching the same conclusion (quoting from pages 31-32):

"As a result, the (basic outphasing) amplifier only achieves its peak efficiency at maximum output power and its efficiency decreases linearly as the output power decreases. This efficiency behaviour is similar to that of a Class A amplifier, which is known to have a very poor overall efficiency ".

It should be noted that the next sentence (p32) , which states**,**

"Of course, the peak efficiency of this (basic) outphasing approach is much higher than that of a Class A amplifier……",

does not in any way redeem the basic judgement on low efficiency, since a modern communications signal reaches its peak value very infrequently, so that the peak power efficiency of an RFPA becomes an almost irrelevant performance parameter. **Note especially the similarity between Figure 1E in this patent and Figure 1.16 (p28) in [3].**

Since this single concept appears to be so central to the PV claims, I have included an appendix (Appendix 1) which analyzes both approaches (conventional linear amplifer, two-input outphasing amplifier), in order to spell out the fact that the PV approach has no basis for claims of efficiency enhancement. I should note that the Chireix style PA has been the subject of much attention in the PA community, with many papers and new patents appearing in the last few years. Even using the Chireix-style combiner, which in principle removes the amplitude variation at each PA output, many problems remain with this approach and it has seen little commercial deployment. In particular, the load modulation on which it depends creates a new source of non-linear effects which are absent in a conventional PA..

The second core claim in the PV patent 7,218,899 is the "MISO", or "Multiple Input Single Output" configuration. This purports to extend the outphasing concept to the use of more than two input signals. This is certainly not new either (e.g. [4,5]). Implementers of the Chireix PA have reported that increasing the number of outphasing signals can have some benefits, such as reducing the range of phase deviation required in each signal input in order to obtain a high dynamic AM range. The MISO is in any case nothing more than a schematic convenience, since all RF power transistors consist of numerous individual cells which may or may not be interconnected for specific applications.

Beyond these core techniques, the PV patents contain vastly detailed mathematical analysis which I read as nothing more than variations on the trigonometric identity taught at high school level,

$$\cos(A)+\cos(B)=2\cos\left(\frac{A+B}{2}\right)\cos\left(\frac{A-B}{2}\right),$$

inasmuch as the core technique refers to a specific case where

$$A = \omega t + \phi_A(t),$$
$$B = \omega t + \phi_B(t),$$

so that

$$\cos(\omega t + \phi_A) + \cos(\omega t + \phi_B) = 2\cos\left(\frac{\phi_A - \phi_B}{2}\right)\cos\left(\omega t + \frac{\phi_A + \phi_B}{2}\right),$$

Which for those who have not done any math since they were at high school, says that the sum of two constant amplitude sinusoidal waves which have the same frequency but a time varying phase difference gives a sinusoidal wave which has both amplitude and phase variation with time. Thus by suitable choice of the input signal phase functions Φ_A and Φ_B, it is possible to construct a signal which has a prescribed amplitude and phase modulated characteristic, a so-called “vector modulated” signal.

The patent then indulges in lengthy and massively detailed embellishments, which in my experience are all standard established techniques in the industry, already widely used to improve the efficiency and linearity of RF PAs. Such techniques as bias adaption and digital predistortion are widely used and specific implementations have themselves been the subject of many patents. Indeed, I cannot help concluding that some of the later PV provisional patents, which further embellish (and mainly repeat) such techniques, in effect contradict the original claims in Patent 7,218,899, admitting that the embellishments have become necessary to compete with existing techniques.

In conclusion, I think it is possible that PV can build a PA system which is based on their core concepts, which will have ***comparable, but not better, efficiency*** than that being routinely obtained and deployed using existing industry-standard PA technology. I believe however, that the ***linearity will be significantly worse at comparable efficiency levels.*** This is based on my own experience developing Chireix-style PAs for WiFi applications. This degradation may respond favourably to linearization, such as digital predistortion (“DPD”). This however will not be an acceptable “fix” in a mobile transmitter application. DPD is now extensively used in high power multi-carrier basestation PAs, and the capabilities and requirements of the digital hardware are well established. In particular, ***a typical DPD system consumes several amps of current*** due to the need for very high speed sampling and processing in such a “real-time” DSP application. Such a drain of power would obviously be unacceptable in a mobile transmitter, especially when current mobile PA products have no need for it. This would nullify one of the most basic claims of Parkervision of high efficiency at low power levels, since as the PA output power drops the power dissipated in the DSP would become even more dominant. It should also be understood that DPD is by no means a universal panacea for PA distortion. In practice, DPD can give a certain maximum amount of linearization, usually measured in terms of the suppression of spectral distortion products. This reduction tends to be the same, regardless of the uncorrected distortion of the target PA. So if the target PA has higher distortion to start with, it cannot be assumed or expected that the final distortion performance will be equal to a system using the same DPD but with a more linear target PA.

My task is to give my own technical asessment on PV's claims, (i.e.) that PV have a "disruptive" revolutionary approach to the implementation of power amplifiers in RF communications systems. My view, which at this time is based entirely on their patents (and by "patents" I am referring primarily to the only issued patent in this area, 7,184,723), is that they don't. However, I have not at this time been able to evaluate hardware demonstration results, which as of the present time of writing I have been unable to access. I have to accept a possibility that their current implementations may not necessarily reflect patent 7,184,723 in its entirety. For example, based on some provisional patents PV have filed, it would seem that in common with the majority of other handset PA vendors, ancilliary techniques such as bias adaption are now being used as well. There is however an additional issue here, in that such results need to have proper "peer review" such as would be the case if PV attempted to publish results in a technical journal or conference. As I stated above, **"eyecatching" efficiency results by themselves mean *nothing***. PA efficiency has to be judged alongside linearity and distortion performance for stipulated signal formats. For example, handset PA modules for the GSM system routinely exhibit over 60% efficiency. But this is specific to a signal format that is already constant envelope. As such, there is nothing new at all in designing PAs that "compress" or even "saturate", giving higher efficiency but being quite unusable.

Some additional qualification is in order concerning linearity performance of PAs, in the light of recent developments in DSP (Digital Signal Processing). With some very important (and not so widely appreciated) limitations, it is possible to reduce the distortion of a PA by suitably "conditioning" the input signal. This is known as "predistortion", and as such has been used for several decades. In older times this predistortion was performed using passive analog networks which were limited in the extent to which they could "cancel" the PA non-linearities. Massive improvements in the speed of digital processors and DAC/ADC converters has more recently enabled modulated RF signals to be processed "on-the-fly". Consequently, given suitable processing speed, and *a priori* knowledge of both the signal itself, the digital approach has greatly increased the dynamic range of possible linearization. Unfortunately, however, this potential "revolution" in PA comes at a price. A typical wireless communication signal has several MHz of bandwidth, and this drives up the clocking and sampling speeds of the digital components. Experience in the high power base station industry shows that the digital predistortion (DPD) of a 10MHz bandwidth signal may require as much as 20 Watts of power to supply the digital hardware. There is also a need for ultra fast digital-to-analog and analog-to-digital converters (DAC, ADC) which require specialized technology and cannot be integrated into commercial CMOS RFIC ("ASIC") processes This all has a significant impact, even for a 200Watt PA, but in the handset application would clearly be impractical and unacceptable.

Consequently, there is scope for misrepresenting PA results when using DPD. In effect, DPD enables the PA to be driven further into its non-linear operating region, thus showing as much as 10-15% efficiency improvement, while the DPD can keep the output distortion down to acceptable limits. **When quoting such a result, it is essential that the power supplied to the DPD is included in the efficiency calculation**. In practice the situation can be even more convoluted than I have described. Most PA manufacturers who make use of DPD use a test bench which is driven by a computer (PC). The PC generates the baseband modulation signal using a mathematical “equation-cruncher” such as MatLab. The various algorithms and formulae for predistorting the raw signal are also implemented by the PC in MatLab. This process can take a number of minutes to complete. The predistorted signal is outputted as a data stream via a USB port and sent to another instrument (an “arbitary function generator”) which then sends a predistorted analog signal to the RF signal generator. Thus the prescribed, predistorted, vector-modulated RF signal is applied to the PA input. The PA, which of course can then be driven to higher efficiency than the same PA when tested using the raw signal, gives much improved efficiency. It is quite common practice (albeit vigorously questioned by reviewers for professional journals and conferences) to quote such improved efficiency numbers without taking account of the power consumed by the PC and the arbitary function generator. It is important also to note, that such a testing procedure will only work for a prescribed signal burst. Change the signal (ie, encode a new data stream) and the predistortion performance will degrade significantly, pending a new computation by the PC. Such results can thus be questioned on more than one front, i.e. not just on whether the DSP power consumption has been included.

In the case of a high power PA used in a cellphone base station, it is reasonable to assume that the processing power of a PC, and the fast, state-of-the-art DAC capability of a modern commercial arbitary function generator, can be implemented as part of the complete radio system. This however cannot be assumed for a handset PA, where current products meet specifications essentially using “raw” signal imputs.

As far as any PV measurement results are concerned, I do not wish to appear to be pre-emptive or to be making allegations about the integrity of their measurement and/or reporting procedures. I am simply making the point that *any* ground-breaking PA results need careful scrutiny and peer review, preferably in a “neutral” environment, in order to make sure that they represent a fair and objective result. This applies most especially when signal sources which generate any kind of pre-conditioned signals are being used.

References

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Appendix 1

Efficiency Analysis of Basic Outphasing PA

Take two RF transistors, with collectors hard-wired together, working into a common RF load (Figure 2). For clarity, the DC bias insertion network has been omitted. This can be regarded as the simplest common denominator of all the configurations cited in the Parkervision patents.

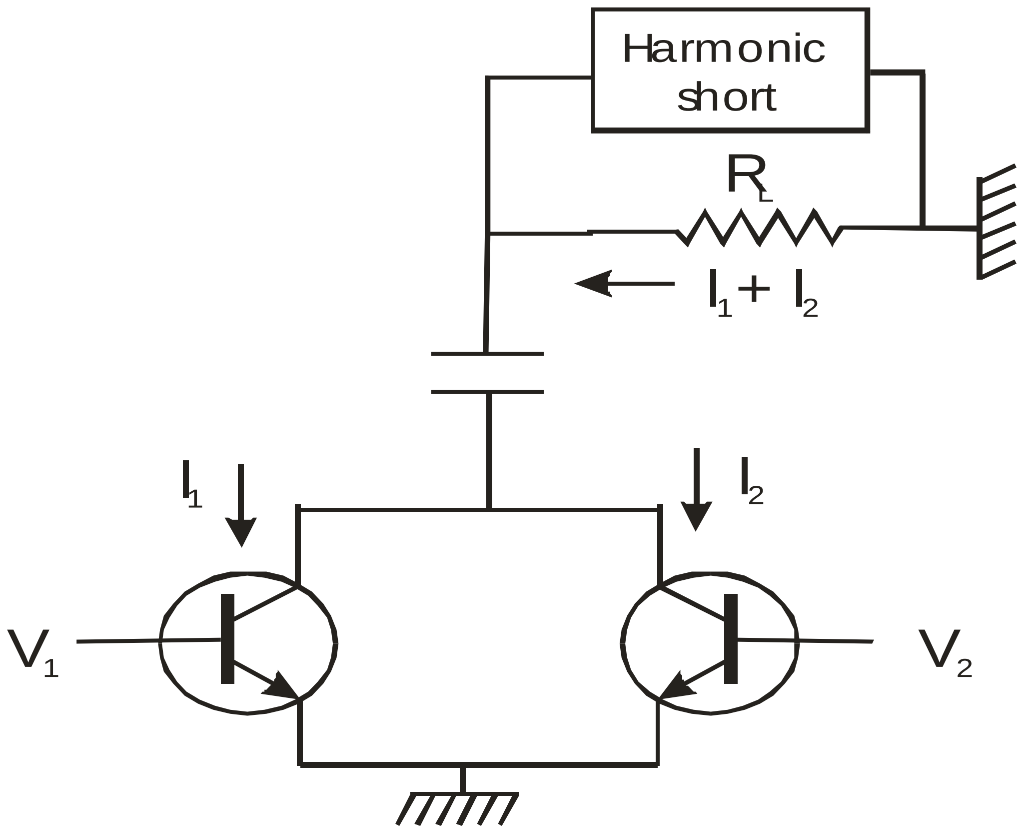

Figure A1. **Basic "outphasing" PA schematic.**

Making the common assumption that the transistor outputs behave as ideal current generators, whose magnitude and phase is directly controlled by the input signals, we can say

$$\begin{aligned} I_1 &= I_{\max}\cos(\omega t + \phi_1) \\ I_2 &= I_{\max}\cos(\omega t + \phi_2) \end{aligned},$$

Where ω is the RF carrier angular frequency, and I_{max} is the stipulated maximum "safe" current for each transistor (this is a common parameter used in the specification of RF power transistors). The phase angles ϕ_1 and ϕ_2 represent the phase modulation on each of the constant envelope driver, or input, signals applied to each device.

So the RF current flowing into the load is

$$\begin{aligned} I_{rf} &= I_1 + I_2 = I_{\max}\{\cos(\omega t + \phi_1) + \cos(\omega t + \phi_2)\} \\ &= I_{\max}\left\{2\cos\left(\frac{\phi_1 - \phi_2}{2}\right)\cos\left(\omega t + \frac{\phi_1 + \phi_2}{2}\right)\right\} \end{aligned}$$

So clearly, by suitable variation of the differential phasing of the two inputs $(\phi_1 - \phi_2)$, amplitude modulation results. The amplitude of the RF current swing can be varied from zero (when $\phi_1 - \phi_2 = \pm\pi/2$), to 2. I_{max} (when $\phi_1 - \phi_2 = 0, \pi$).

A key aspect of PA design is the choice of load resistor value. Conventionally, this resistor is chosen such that the maximum voltage swing is obtained at a stipulated maximum RF current swing. The maximum voltage swing is taken to be the DC voltage bias level, V_{dc}, since any higher RF swing would cause clipping and severe distortion of the amplitude modulated signal we are creating. So in this case the logical choice would be to select a value such that

$$R_L = \frac{V_{dc}}{I_{\max}},$$

the numerator and denominator representing the maximum allowable amplitudes of sinusoidal RF voltage and current swings, respectively.

If for the time being, we assume a Class A amplifier, the current bias will be set to a value which is half of the peak sinusoidal current swing, I_{max} in this case for two combined transistors each having an individual maxiumum swing of I_{max} .

When the phasing of the inputs is such that the current swing in the RF load is at a maximum value of 2 I_{max} , the RF power dissipated in the load can be expressed as

$$P_{rf} = \frac{V_{dc} I_{\max}}{\sqrt{2\sqrt{2}}},$$

this being the product of the RMS amplitudes of the RF current and voltage swing. The corresponding power supplied by the DC bias supply is

$$P_{dc} = V_{dc} I_{\max},$$

So the output efficiency of the configuration, which is the output RF power divided by the DC supply power, is

$$\eta = \frac{P_{rf}}{P_{dc}} = \frac{1}{2},$$

Or 50% as efficiency is usually expressed.

If however the phasing of the inputs is such that the amplitude of the current swing has dropped by a factor of 2 (corresponding to a differential input phasing of 60 degrees), the RF output power will drop to a value

$$P_{rf} = \frac{V_{dc}}{2\sqrt{2}} \cdot \frac{I_{\max}}{2\sqrt{2}},$$

or the maximum power divided by a factor of 4. This result confims the required amplitude modulation capability of the configuration. The phasing of the input signals controls the combined output current swing, in this case causing an amplitude modulation factor of 6dB. *The efficiency however will drop by the same amount,*

$$\eta = \frac{V_{dc} I_{\max} / 8}{V_{dc} I_{\max}} = \frac{1}{8},$$

or 12.5%.

The key point is that the outphasing action reduces the current, which then causes a correspondingly lower voltage swing across the RF load. Thus energy is wasted by having a voltage across each device which never reaches zero. **So this configuration has exactly the same "efficiency backoff" problem which is encountered in conventional PA designs.** As the outphasing does its work the RF amplitude is reduced, as intended to create AM, but the voltage swing at each device also drops, causing a major efficiency drop as well. Conventional methods for alleviating this problem usually involve a scheme whereby the load impedance itself is reduced as the RF current swing is reduced. This is a key ingredient in both the Doherty PA and the Chireix outphasing PA.

In the interests of simplicity, the above analysis refers to a Class A bias. In a conventional RFPA, the devices would normally be biased to a very low standing current (Class B). This increases the efficiency at peak power level (to 78.4%) and also improves (but does not eliminate) the efficiency degradation as the RF power is reduced (usually referred to as "Power Back-off, or PBO). In this patent, the use of higher efficiency modes such as Class B,D,E,F are mentioned. I note however that no provisions are made in the many block diagrams to ensure that the necessary harmonic terminations are provided at the device outputs (harmonic networks on the input are mentioned, but not in this context). Even in this case, however, the above analysis for the Class A case would have the same conclusion for Class B bias; the outphasing approach would have the same PBO efficiency as a conventional PA.

The waveforms shown in figure A2 illustrate the above analysis more graphically. The outphasing pair approach (claimed, in essence, by PV as their invention but in fact dating at least from the 1930's) is compared directly to a conventional approach, using Class B bias in both cases. In order to make a fair comparison, the Class B case is illustrated with the same two devices connected directly in parallel (V_1=V_2 in Fig.A1) , in comparison to the outphasing pair which are excited by input signals which have the same amplitude but a differential phase difference. The key point is that despite the different input signal arrangements, the **voltage and current waveforms which appear at the output load resistor are the same in each case**, both in terms of the RF power, and also the orientation of the RF voltage about the DC supply level. This applies both for the peak power case (left hand frames) and a typical case of backed-off power (6dB in this example). So the efficiency of the outphasing pair is the same as the Class B approach, and thus offers **no benefit in terms of efficiency**.

It should also be noted that any attempt to drive the individual devices into saturation by allowing the voltage to clip on the supply rails will effectively invalidate the assumption that the individual devices behave as current generators which can be summed in a single common load resistor. A voltage-clipping PA device in fact behaves more like a voltage source (see Cripps, [3], chapter 10) and the output of two such devices can no longer be “summed” by hard-wire parallel connection.

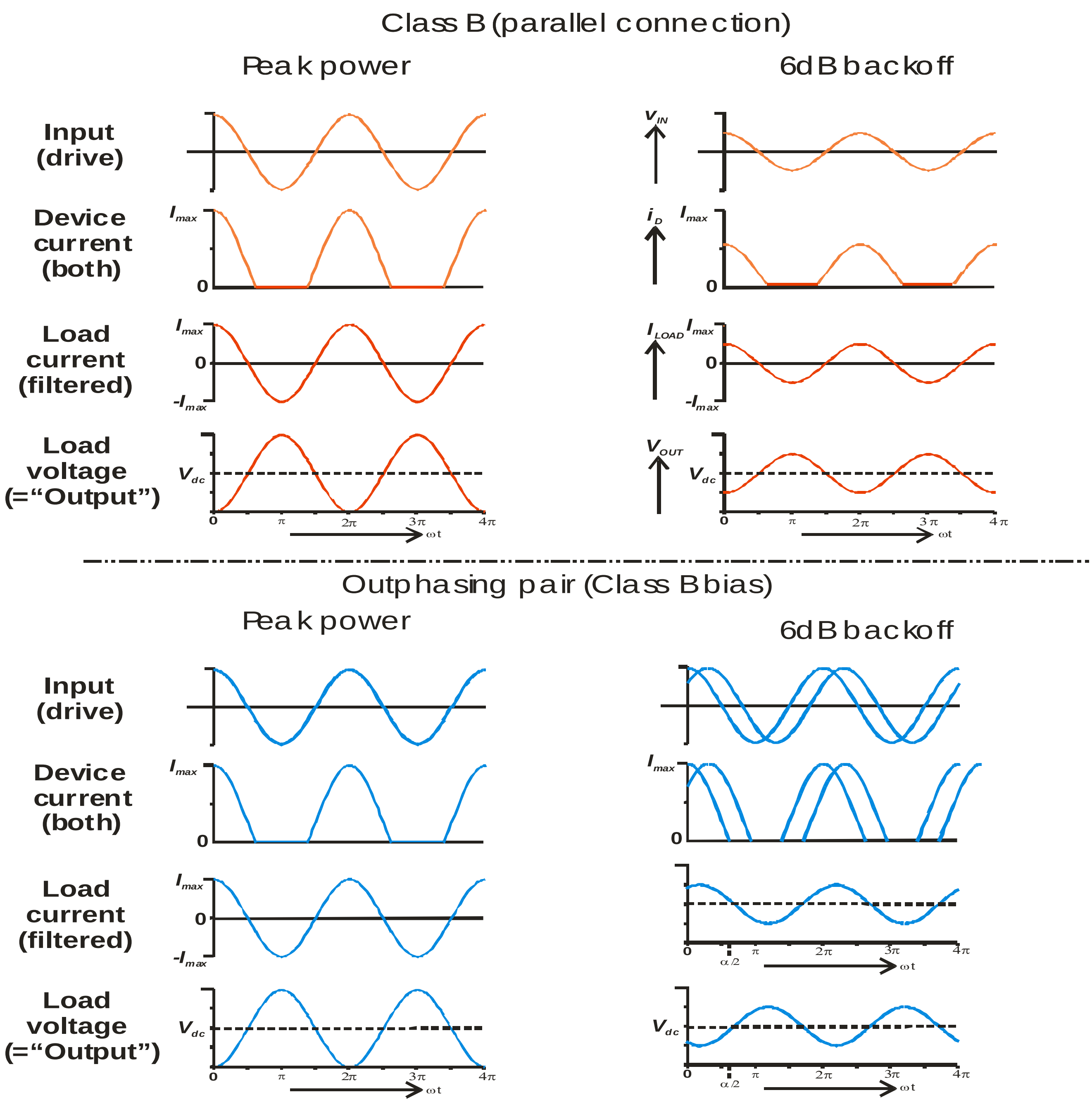

Figure A2. Voltage and current waveforms for conventional Class B PA (Upper, red) and outphasing pair (lower, blue), for peak power condition (left) and 6dB backed-off condition. Load current traces (third down in each case) assume a harmonic short has been placed across the load resistor, allowing just fundamental current and voltage to appear.