## APPLICATION NOTE 70

# INJECTION POWER SAVINGS IN HYBRID LOAD PULL

## Introduction

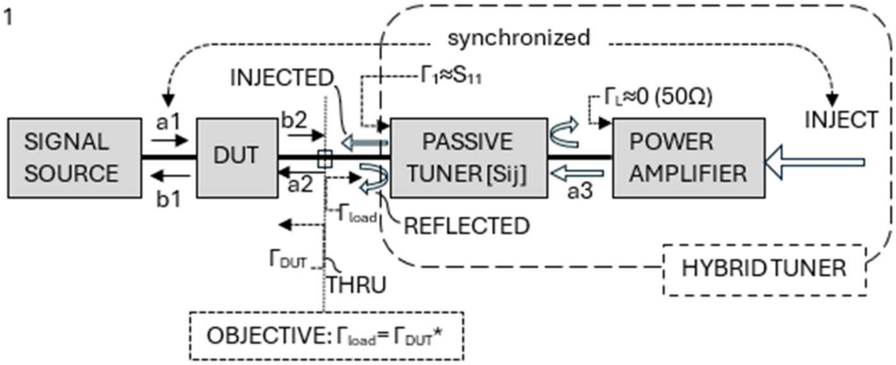
Load Pull or Source Pull is the systematic RF (and DC) characterization of a device under test (DUT, transistor) for a selected set of load (or source) impedances Z or reflection factors Γ=(Z-Zo)/(Z+Zo). The device used to create and control Γ is called a *tuner*. A tuner can be an instrument or a condition; both create signal that is returned to the DUT; if the returned signal is created by reflection on a mechanical obstacle (tuning probe or slug) we speak of a *passive tuner*; if it is created by injecting synchronized signal through feedback or by external signal source we speak of an *active tuner*; if it is created by both active and passive method we speak of a *hybrid tuner*. Active or hybrid tuners are necessary if a passive (mechanical) tuner cannot reach (due to hardware limitations) the conjugate ($Z_{DUT}$*) of the DUT impedance $Z_{DUT}=R_{DUT}+jX_{DUT}$; this happens for very large (high-power) or very small (low noise) transistors with extremely small or large internal impedance ($|\Gamma_{DUT}|\approx1$).

## Summary

As already said, the main objective of load pull is to conjugate match the DUT to extract maximum power or maximize efficiency. This can be done by either mapping an area of or the entire Smith chart with selected impedances and extract the information graphically (Load Pull contours) or by using peak search routines with user-set objectives (maximum power, maximum efficiency, linearity etc.). In the case of passive or active load pull the search is straight forward: the quantity in question is measured and the impedance is changed using a gradient iterative method until the quantity is optimum. This is abundantly described in Application Note 22 (Peak search routines…) of Focus Microwaves.

In the case of hybrid load pull, though, the situation is more complex (Fig. 1):

Fig. 1



In the pure passive tuning configuration, the reflection coefficient seen by the device is expressed as: $\boldsymbol{\Gamma}_{load} = \frac{a_2}{b_2} \approx S_{11}$. As passive tuners and associated adapter losses may not reach extremely high load reflection coefficients, to conjugate match a high $|\Gamma_{DUT}|>0.95$, an assisting active injection $P_{inj}$ will be needed.

In the pure active injection tuning configuration, where we do not use a pre-matching tuner, the relative power the PA must provide is: $\frac{\boldsymbol{P}_{inj}}{\boldsymbol{P}_{DUT}} = \frac{|\boldsymbol{\Gamma}_{DUT}|^2}{1-|\boldsymbol{\Gamma}_{DUT}|^2}$. This value reaches infinity as $|\Gamma_{DUT}| \to 1$. For example, in a realistic scenario of purely resistive power transfer with $\boldsymbol{\Gamma}_{DUT} = \frac{\boldsymbol{R}_{DUT}-50}{\boldsymbol{R}_{DUT}+50}$, and $\frac{\boldsymbol{P}_{inj}}{\boldsymbol{P}_{DUT}} = \frac{(\boldsymbol{R}_{DUT}-50)^2}{200*\boldsymbol{R}_{DUT}}$, the required injection power for $R_{DUT}=1\Omega$ $[\Gamma_{DUT}=0.961]$, $P_{DUT}=10W$ *is* $P_{inj}\approx 120W$ or 11dB higher! When $\Gamma_{DUT}\approx 0$, then $P_{inj}\approx 0$. This $P_{inj}/P_{DUT}$ *ratio is depicted in Fig. 2:*

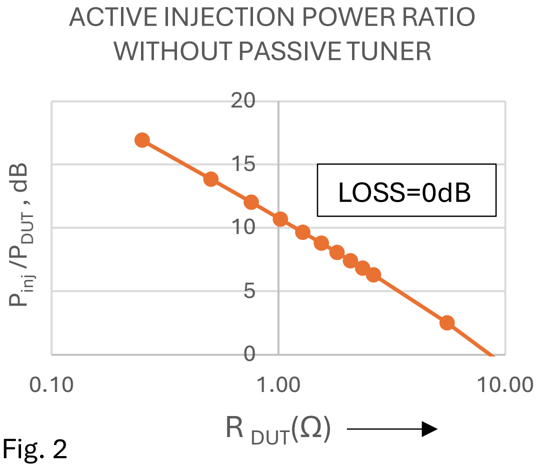
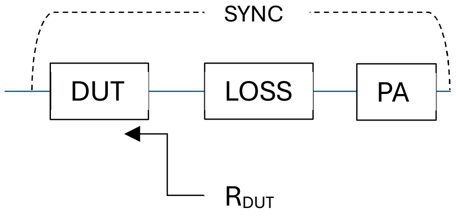


Fig. 2



In the hybrid configuration presented in Fig. 1: $P_{inj} = \frac{|\boldsymbol{a}_3|^2}{2}$, and $P_{DUT} = \frac{|\boldsymbol{b}_2|^2}{2}$. For conjugate matching $\boldsymbol{\Gamma}_{load} = \boldsymbol{\Gamma}^*_{DUT}$ and to increase the reflection coefficient seen by the device $\boldsymbol{\Gamma}_{load}$ beyond $\boldsymbol{S}_{11}$ of the tuner, we combine the DUT signal reflected by the tuner $b_2.\boldsymbol{S}_{11}$ with another coherent signal provided by the PA and pre-matched by the same tuner. The total available power wave is $a_2 = b_2.\boldsymbol{S}_{11} + a_3.\sqrt{\boldsymbol{G}_{av.t}}$ which contains the additional coherent wave component with the magnitude of: $\sqrt{\boldsymbol{G}_{av.t}}.a_3$, where:

$$\boldsymbol{G}_{av.t} = \frac{|\boldsymbol{S}_{12}|^2.(1-|\boldsymbol{\Gamma}_{DUT}|^2)}{(1-|\boldsymbol{S}_{11}|^2)}.$$

The S-parameters of the tuner depend on the tuner status and since our goal is to reach $\boldsymbol{\Gamma}_{load}=\boldsymbol{\Gamma}_{DUT}^*$ with a <u>minimum</u> of injected power $\boldsymbol{a}_3$ (and amplifier cost), we should position the tuner such that the ratio $\frac{\boldsymbol{a}_2}{\boldsymbol{b}_2} = \boldsymbol{\Gamma}_{load} = \boldsymbol{\Gamma}_1 + \frac{a_3}{b_2}\sqrt{\boldsymbol{G}_{av.t}} = \boldsymbol{\Gamma}^*_{DUT}$ yields tuner S-parameters for which $\boldsymbol{a}_3$ is minimum as shown in this equation:

$$\frac{|\boldsymbol{a}_3|^2}{|\boldsymbol{b}_2|^2} = \frac{\boldsymbol{P}_{inj}}{\boldsymbol{P}_{DUT}} = \frac{|\boldsymbol{\Gamma}^*_{DUT} - \boldsymbol{\Gamma}_1|^2}{\boldsymbol{G}_{av.t}}$$

$$\approx \frac{|\boldsymbol{\Gamma}^*_{DUT} - \boldsymbol{S}_{11}|^2.(1-|\boldsymbol{S}_{11}|^2)}{|\boldsymbol{S}_{12}|^2.(1-|\boldsymbol{\Gamma}_{DUT}|^2)} \to \boldsymbol{min}.$$

This relation determines the required injection power $|\boldsymbol{a}_3|^2/2$ for a DUT output power $|\boldsymbol{b}_2|^2/2$ and a DUT output reflection factor $\boldsymbol{\Gamma}_{DUT}$, if the DUT housing, fixturing (wafer probes) and setup components are all included in the tuner S-parameters $[S_{ij}]$. This relationship shows us that if the tuner can reach $\Gamma_1\approx S11\approx\Gamma_{DUT}*$, then there is no need for active tuning. In hybrid tuning, if for instance we target $P_{inj}=P_{DUT}$, the relation between $\Gamma_{TUNER}$ and $\Gamma_{DUT}$ is shown in Fig. 3.

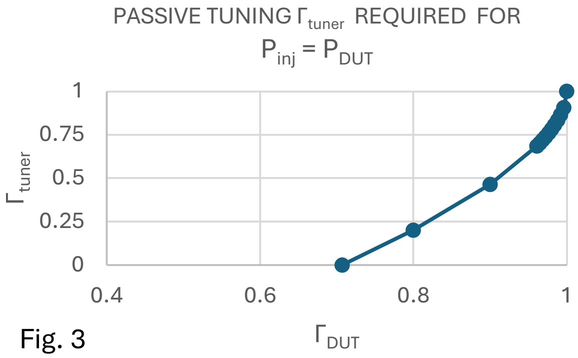


Fig. 3

So, it is logical to push an ideal tuner reflection coefficient as high as we can. However, since in a real case $\Gamma_{tuner}$ cannot reach 1 because of insertion and fixture loss, active injection will be needed.

The following Fig. 4 compares multiple scenarios to obtain $\boldsymbol{\Gamma_{DUT}}$=0.961. The red dotted curve is a theoretical curve that assumes a lossless tuner. It shows that if the tuner can attain 0.961 then $\boldsymbol{P_{inj}}$ → 0 and no active injection is needed. The other two solid curves represent hybrid tuning with realistic scenarios where the losses including fixture and tuner access are assumed to be 0.5 and 1.5dB respectively, which represent a setup with DELTA tuner and setup with regular tuner and cables.

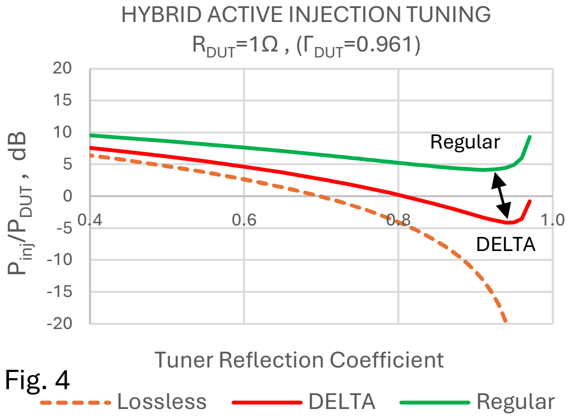


Fig. 4

We can easily notice that as we push the tuner to a higher VSWR, we can achieve $\boldsymbol{P_{inj}}$ power saving over the pure active scenario of as much as 8dB using a regular tuner and about 15dB when we use a Focus DELTA tuner.

We can also see that assuming a constant tuner loss (reflection and dissipation) is misleading. The optimum solution is a compromise between S-parameters (reflection versus loss) of the tuner and the internal impedance of the DUT.

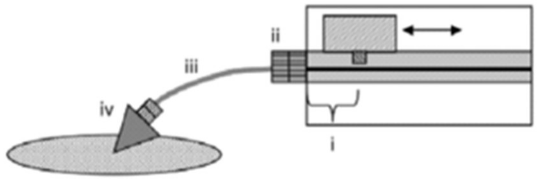
**Search strategy to lower injected power.**

Since tuner loss cannot be theoretically assumed, the primary search tool is, obviously, the passive tuner cal file.

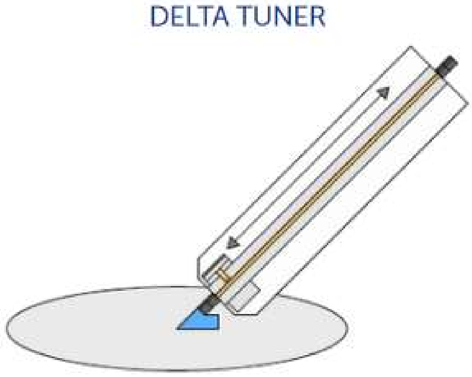
The injected power $\boldsymbol{a_3}$ traverses a minimum value for every combination of DUT output power $\boldsymbol{b_2}$ and output impedance $\boldsymbol{\Gamma_{DUT}}$. The actual value of $\boldsymbol{P_{inj}}$ depends on the setup and the tuner used and is not DUT specific, like ordinary load pull contours, it is a system specific quantity, that also depends on the DUT. <u>Since we deal with an unknown DUT</u> we proceed as follows: **(1)** find out if passive tuning is sufficient ($|\boldsymbol{S_{11}}| \geq |\boldsymbol{\Gamma_{DUT}}|$); i.e. we measure $\boldsymbol{b_2}$ and $\boldsymbol{a_2}$ on a maximum $\boldsymbol{S_{11}}$ circle via a bidirectional coupler and stop at $\boldsymbol{S_{11.max}}=\boldsymbol{\Gamma_{.max}}$ for $\boldsymbol{a_{2.max}}$; if $\boldsymbol{a_{2.max}} \geq \boldsymbol{b_2}$ then the specific DUT can be matched with the tuner at hand. If $\boldsymbol{a_{2.max}} < \boldsymbol{b_2}$, then we need active injection $\boldsymbol{a_3}$ **(2):** from $\boldsymbol{\Gamma_{max}}$ we increase $\boldsymbol{a_3}$ by small steps and scan the angle < $\boldsymbol{a_3}$ until we reach $\boldsymbol{a_2}=\boldsymbol{b_2}$; to find the minimum $\boldsymbol{a_3}$ we reduce $\boldsymbol{S_{11}}$ from $\boldsymbol{S_{11.max}}$ by small steps in a loop and search again for a new $\boldsymbol{a_3}$ for which $\boldsymbol{a_2}=\boldsymbol{b_2}$; the loop lasts as long as $\boldsymbol{a_3}$ decreases; when $\boldsymbol{a_3}$ starts rising again, the last found $\boldsymbol{a_3}$ is the minimum injected power needed to conjugate match the DUT with the actual tuner at its present condition.

## The impact of DELTA tuners

On-wafer testing requires RF cables between the probes and the tuner shown as items I, II, III, IV in the picture below.



The increased insertion loss between the probe tip and the tuner slug demands higher and critical internal tuner $S_{11}$. To minimize the insertion loss, we bring the tuning probe (slug) as close to the wafer probe as physically possible, and this is what DELTA tuners do.



The result is lower insertion loss between wafer probe and tuning probe (slug) with dramatic effects not only on maximum Gamma at DUT reference but also higher tuning accuracy (see PN #94) and lower injected power in a hybrid load pull configuration.

The use of DELTA tuners in hybrid injection provides several benefits in terms of power level savings and reduction of measurement errors.

## Hybrid tuning power saving:

The table below uses the available power gain calculations depicted earlier. It shows the power needed to match $|\Gamma_{(DUT)}|$ ranging between 0.8 and 0.981 with a $|\Gamma_{TUNER}|=0.8$. We can see that the pure active Load Pull requires an injection power ranging from 3dB to 14.3dB above the DUT power level. The power savings in a hybrid setup with a regular tuner is about 6dB, while the same setup with a DELTA tuner provides at least 10dB of power saving.

| $P_{inj}/P_{DUT}$ | Pure Active | Regular Hybrid, **Γ(Tuner)=0.8** | DELTA Hybrid **Γ(Tuner)=0.8** |
|---|---|---|---|
| Γ(DUT)=0.80 | +3.0 dB | -6.0 dB | -16 dB |
| Γ(DUT)=0.85 | +4.4dB | -3.0 dB | -10.5 dB |
| Γ(DUT)=0.9 | +6.5 dB | -0.2 dB | -6.2 dB |
| Γ(DUT)=0.951 | +10.0 dB | +4.0 dB | -1.1 dB |
| Γ(DUT)=0.961 | +11.0 dB | +5.2 dB | +0.2 dB |
| Γ(DUT)=0.981 | +14.3 dB | +8.7 dB | +4.0 dB |

## Reduction of measurement error:

As tuner s-parameter measurement error on both S11 and S21 is estimated to be -60dB (±0.0005), a lossless tuner hybrid assembly yields a potential measurement uncertainty (error) of -48dB.

Accounting for realistic cable loss when a regular tuner is connected, the potential error is estimated to be -38dB. When a DELTA tuner is used instead, the potential error is estimated to be -46dB, which represents an 8dB of improvement. This improvement is due to lower internal $S_{11}$ and means that DELTA tuners inherently offer an accuracy improvement without farther calibration accuracy expense. These results are summarized in the table below for $|\Gamma_{DUT}|=0.8$.

| Tuner Setup | Γ (Tuner) | Error |
|---|---|---|
| Regular | 0.95 | -38 dB |
| DELTA | 0.85 | -46 dB |
| Lossless | 0.80 | -48 dB |