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Designing Power Amplifiers for Spectral Compliance Using Spectral Mask Load-Pull Measurements

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***Abstract*— This paper demonstrates power amplifier design using load-pull measurements to determine spectral mask compliance as a function of load impedance. In most cases demonstrated in the open literature, the spectral spreading of the device is indirectly assessed by a metric such as the adjacent-channel power ratio or third-order intermodulation product. In the present paper, a spectral mask compliance metric is introduced that is less than or equal to zero for compliant spectra and positive for non-compliant spectra. The paper first examines the load-pull measurement for the spectral mask compliance metric, including the use of averaging to smooth the contours. Direct, dual-objective design of power amplifiers for spectral mask compliance and efficiency is then demonstrated by choosing the load impedance that provides the highest measured power-added efficiency while maintaining spectral compliance. With the device terminated in the chosen optimum impedance, measurement of the output spectrum and comparison with a spectral mask are performed to demonstrate spectral compliance at the selected design impedance.**

***Index Terms*— power amplifiers, impedance, radio spectrum management, energy efficiency, linearity.**

I. Introduction

Load-pull measurements are used by power-amplifier designers to assess the variation of certain device metrics with load impedance. Both the linearity and efficiency of a power amplifier are dependent on the load impedance presented to the active device. Sevic demonstrates load-pull tuning for adjacent-channel power ratio (ACPR) [1-2]. ACPR measures the ratio between power in a defined adjacent band to the in-band power, and has been significantly used to assess the dependence of unwanted spectral spreading on the load impedance. Wu shows that spectral spreading in amplifiers is caused by third- and fifth-order intermodulation distortion (IM3, IM5) [3].

There is a disconnect between ACPR or IM3 measurements and regulatory settings. Most regulations of the wireless spectrum are given in terms of spectral mask criteria. Spectrum is internationally regulated by the International Telecommunication Union (ITU). In the United States, the spectral mask is assigned by the Federal Communications Commission (FCC) and the National Telecommunications and Information Administration (NTIA). Standards such as ITU-R SM.329 [4] and ITU-R SM.1541 [5], the ITU Radio Regulations [6], and the NTIA Radar Spectrum Engineering Criteria [7] discuss allowable spectral emissions. Davidson et al. have proposed a spectral-mask optimization with linear matrix inequalities, demonstrating the optimization in filter and beamformer design [8]. Parr [9], Sheng [10], and Luo [11] present waveform optimization to spectral mask criteria. De Graaf et al. discuss the need for radar transmission to be spectrally confined and present design ideas [12].

The present paper provides a solution to the disconnect between typical load-pull measurements used for power-amplifier design and assessing the ability of a design to comply with spectral mask requirements. A previous paper from our group introduces a spectral mask compliance metric [13]:

$$S_m = max(s - m), \qquad (1)$$

where s is the measured power from the spectrum analyzer in dBm, and m is the power of the spectral mask at the same frequency, also in dBm. If $S_m \leq 0$, then the spectrum is in compliance with the mask, and if $S_m > 0$, then the spectrum is out of compliance. The previous paper focuses on a fast search algorithm to find a constrained optimum [13], but does not demonstrate measurement of the S_m contours or discuss the use of S_m contour measurement in design. The present paper demonstrates, for the first time, measurement of the S_m load-pull contours and the use of S_m contours with power-added efficiency (PAE) contours to directly design power amplifiers for spectral mask compliance. Measurement and design considerations are discussed.

II. Load-Pull measurements for Spectral mask Compliance

Figure 1 shows the load-pull measurement test setup used to perform load-pull measurements of the spectral-mask compliance metric S_m. An Agilent signal generator was used to generate the test waveform (for the measurements shown, a frequency-modulated chirp waveform in combination with a tone was used), and the Agilent spectrum analyzer and power meter/sensor were used to measure the spectrum and the output power, respectively. A mechanical load-impedance tuner from

Maury Microwave was used to vary the load reflection coefficient Γ_L presented to the device. The source tuner pictured in the setup was not used for these experiments.

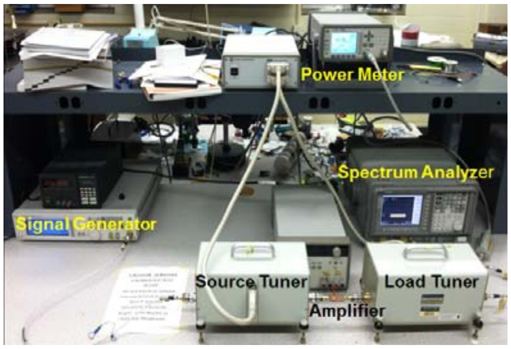


Fig. 1. Measurement test bench

As with typical load-pull measurements, a grid of pre-determined Γ_L values was selected for measurement. MATLAB code was created to control the load-pull measurement directly, and contours were fit to the data. Figure 2 shows measured S_m contours for a Skyworks packaged amplifier using this test setup. For comparison, Figure 3 shows ACPR contours for the same device. Comparing Figures 2 and 3 shows that, while the S_m and ACPR contours possess similar shapes and characteristics, the ACPR contours are smoother than the S_m contours. This is because the total (summed within the channel) powers measured by the spectrum analyzer at all points within the defined main and adjacent channels are used for the ACPR measurement, while the S_m value is based on a measurement at *only one frequency point* (the frequency that has the highest spectrum value relative to the mask). As such, ACPR measurements involve a built-in type of averaging, while S_m measurements are single-point. To decrease the artifacts of measurement variation and noise in the S_m characteristics, averaging can be used. Figure 4(a) shows the S_m contours from data averaged over two measurements, and Figure 4(b) shows the results of averaging over three measurements. Comparing Figs. 2, 4(a), and 4(b), it is seen that as the number of measurements that is used for the averaging increases, the S_m contours grow smoother.

When using S_m load-pull measurements for amplifier design, the Smith Chart can be divided directly into regions of spectrum-compatible and spectrum-incompatible Γ_L values. Figure 5 shows the PAE contours for the Skyworks amplifier, along with the S_m contours and region of spectrum compatibility ($S_m \leq 0$). It can be seen that the highest PAE value obtainable under spectral mask requirements can be achieved by selecting $\Gamma_L = 0.55\underline{/-30.52}°$. As in most design cases, this constrained optimum occurs on the boundary of the compliant region. As such, knowing exactly where that boundary exists allows a higher efficiency to be achieved, because no guesswork is involved in the relationship of ACPR to spectral compliance. To verify the spectral mask compatibility of the design choice, Figure 6 shows the measured power spectrum at the chosen design reflection coefficient, $\Gamma_L = 0.55\underline{/-30.52}°$. It can be seen that the spectrum appears compatible with the mask.

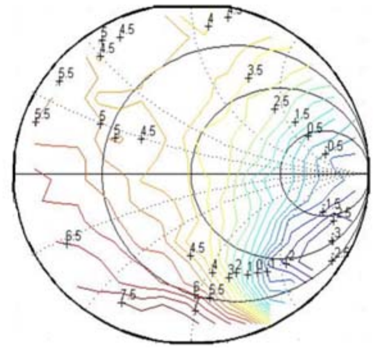


Fig. 2. Measured S_m load-pull contours for the Skyworks amplifier. Values of S_m are indicated in dB.

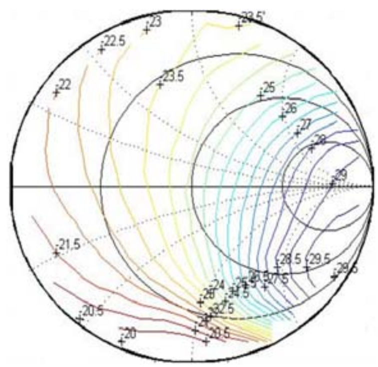
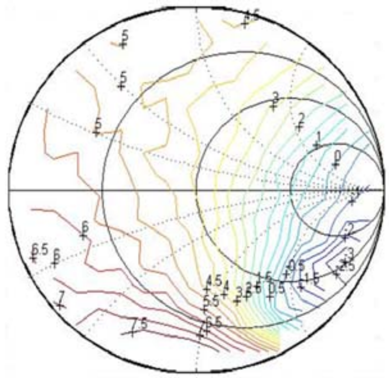


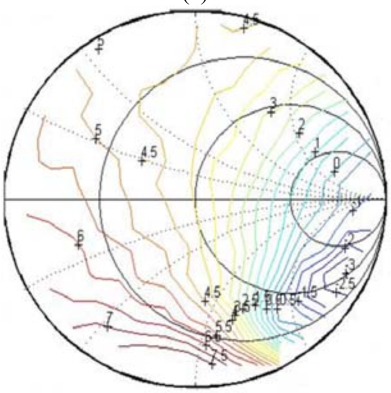
Fig. 3. Measured ACPR load-pull contours for the Skyworks amplifier. Values of ACPR are indicated in dBc. The ACPR and S_m characteristics are similar in shape and in optimum location. The ACPR contours are less jagged than the S_m contours due to the inherent averaging of the ACPR measurement.

III. Conclusions

A procedure for directly designing power amplifiers for spectral compliance has been demonstrated using load-pull measurements for a spectral-mask compliance metric. In a design example, the value of reflection coefficient providing the highest PAE while maintaining $S_m \leq 0$ was selected. A spectrum measurement of the amplifier output using this termination was performed to verify the spectral compliance of the design. The load-pull measurement of the spectral mask metric S_m has been compared with the more traditional spectral-spreading load-pull characteristic of ACPR, and it is seen that the contours have similar characteristics. Performing S_m load-pull will allow power-amplifier designers to directly assess spectral mask compliance.



(a)



(b)

Fig. 4. Measured S_m load-pull contours for the Skyworks amplifier averaged over (a) 2 measurements and (b) 3 measurements.

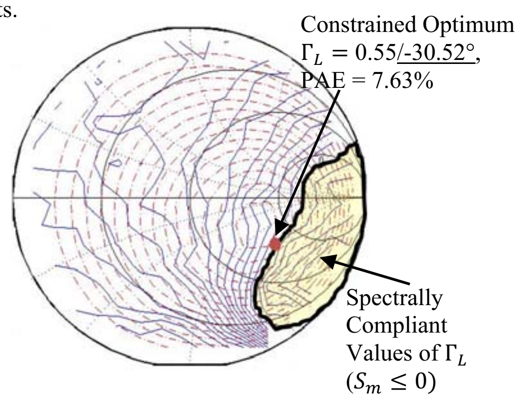


Fig. 5. Measured S_m (solid contours) and PAE (dashed contours) load-pull contours for the Skyworks amplifier, with the spectrum-acceptable region taken from the measured S_m load-pull data ($S_m \leq 0$) shaded. The constrained optimum Γ_L is shown.

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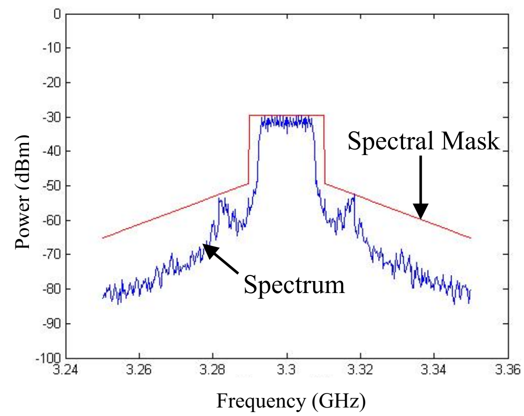

Fig. 6. Measured spectrum and spectral mask at the chosen design reflection coefficient $\Gamma_L = 0.55\underline{/-30.52}°$. As expected, the spectrum meets spectral constraints.

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