Dual-band Switching Doherty Power Amplifier using Phase Shifter Composed of PIN Diode

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Abstract — **In this paper, a new method for improvement of the efficiency of Doherty power amplifier (PA) at dual-frequencies is presented. The structure of the conventional Doherty PA using equal LDMOS devices for main Class-AB and peaking Class-C amplifiers is designed. Compensation line with phase shifter composed of PIN diode is adapted and demonstrated experimentally for removing reactance components of the output impedance at each frequency. Adequate output phase of the Doherty PA at each frequency is adjusted using switching operation of PIN diode. In order to evaluate the switching performance of the proposed method, measurements have been carried out at two sample frequencies (2.1 GHz and 2.2 GHz). According to the on- (2.1 GHz) and off-state (2.2 GHz) of PIN diode, compensation line adjusts exact load impedance at each frequency. The proposed 100 W Doherty PA provides power added efficiency (PAE) over 47% at 6-dB back-off power region (44 dBm). At 2.1 GHz, Doherty PA at on-state shows about 5% enhancement of PAE comparison with Doherty PA at off-state.**

Keywords **- Doherty amplifier; multi-band; phase shifter; PIN diode; power added efficiency**

I. INTRODUCTION

Due to the use of a modulated signal, which usually have a large signal bandwidth and a high peak-to-average ratio (PAR) to transmit high data rate signals for numerous multimedia communications, modern communication systems require multi- and broad-band operations for providing lots of services. Each component used these system is also required better performance for multi- and broad-band operations. Power amplifier (PA) is one of the major parts to decide performance and cost of the system. Therefore, PA has to achieve high efficiency characteristics with low distortion to attain the spectral mask requirements and to avoid amplitude clipping such signals. Hence, linear characteristic of the PAs is highly demanded for the base stations.

The efficient characteristic of the PA is also required not only at the peak power but also within the whole dynamic range, which could get to 12 dB PAR nowadays. This becomes particularly challenging since the high PAR requires large amounts of back-off operation. When a standard single stage PA is implemented, a PA at large back-off operates with little efficiency and low efficiency of the PA will inherently affect the capital expenditure and operational cost of the system.

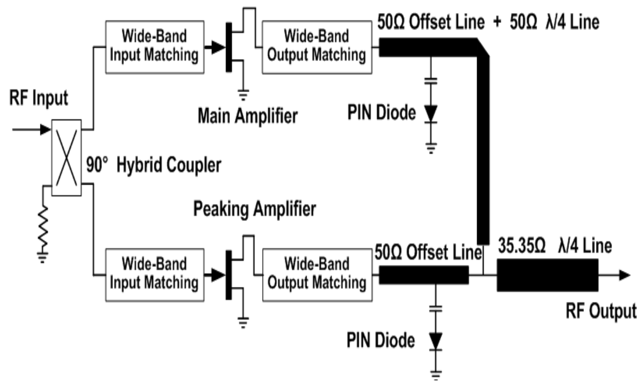


Fig. 1. Schematic of the dual-band switching Doherty PA.

Therefore, the PA design activity becomes increasingly challenging to satisfy a linearity specification for stable communication with higher efficiency. To optimize the efficiency-linearity trade-off, various PA architectures have been investigated in the past few years such as LINC (Linear Amplification using Non-linear Component), EER (Envelope Elimination and Restoration), ET (Envelope Tracking), Doherty. Among others, the Doherty PA technique has been in particular a front candidate due to its simple circuitry [1-2].

However, the Doherty technique is based on load modulation at single frequency and has a narrow bandwidth. Although Doherty with EER technique [3] or varactor diode [4-5] are proposed for the improvement of bandwidth, the former has a very complex circuitry which leads to a heavy outlay and the latter is only suitable for a low-power operation. This paper presents a new design method for dual-band switching operation of the high power Doherty PA. With a PIN diode, the compensation line is designed for the exact load modulation at each frequency. The proposed Doherty PA as shown in Fig. 1 has two different operations according to the state of diodes and shows over 47% of PAEs at 6-dB back-off region at on-state 2.1 GHz and off-state of 2.2 GHz.

II. STRUCTURE OF PHASE SHIFTER WITH PIN DIODE

At radio frequency (RF), high voltage PIN diode has impedances that vary essentially from a short circuit at forward bias to an open circuit at reverse bias when referred to a 50 ohm transmission line impedance and characteristics of on- and

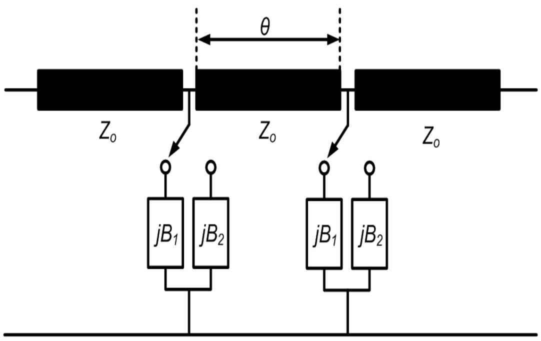


Fig. 2. Basic circuit of the loaded line phase shifters.

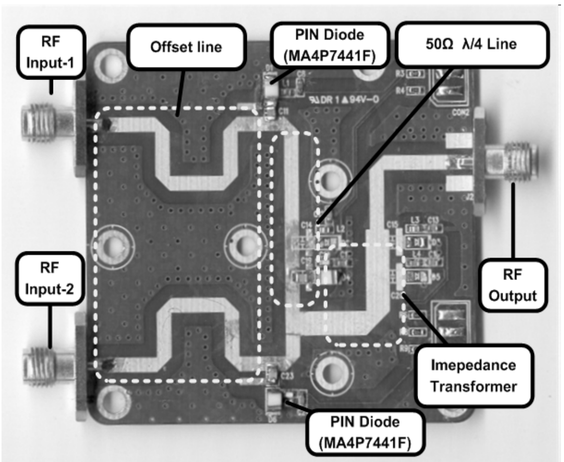


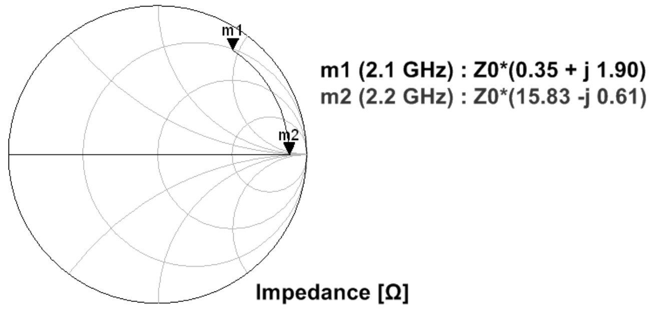
Fig. 3. Fabricated compensation lines with phase shifters.

off-operations such as switch. With this operation of diode, the concept of phase shifter was presented by [6].

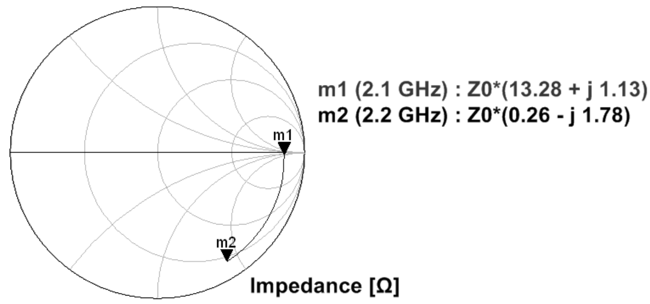
The loaded-line phase shifters as shown in Fig. 2 is adapted with PIN diode. Open-circuit diodes will introduce a positive susceptance B_N and a large phase delay Φ_{DO}, while short-circuit diodes will give a negative susceptance B_N with small phase delay Φ_{DO}. The phase shift is given by

$$\Delta\phi = \phi_{DO} - \phi_{DS} = 2\tan^{-1}\left[\frac{B_N}{1-0.5B_N^{\ 2}}\right] \qquad (1)$$

On the basis of above concept, phase shifter circuit which consists of compensation lines, PIN diodes (MA4P7441F), quarter-wavelength 50Ω and 35Ω transmission line is designed and fabricated as shown in Fig. 3. The substrate is a Taconic RF-35, which has a dielectric constant of 3.5, a substrate thickness of 0.762 mm and dissipation factor of 0.0018 at 2.2 GHz. The compensation line is followed by two PIN diodes and a state of diode cause the variation of output phase of PA. Peaking bias point of Doherty PA and compensation line length are optimized to obtain an accurate load modulation at 2.2 GHz so that the output impedance of the peaking amplifier at the combining point is almost open at a low power region. As diode is turned on, compensation line begins to adjust output phase and the output impedance of the peaking amplifier at the combining point becomes almost open at 2.1 GHz. Fig. 4 shows the variation of the output impedance of the peaking amplifier according to the change of diode state. The output phase differences between main and peaking amplifier at each state are shown in Fig. 5. By turning on the diode, the frequency with 90 degree phase difference is changed from 2.2 GHz to 2.1 GHz.

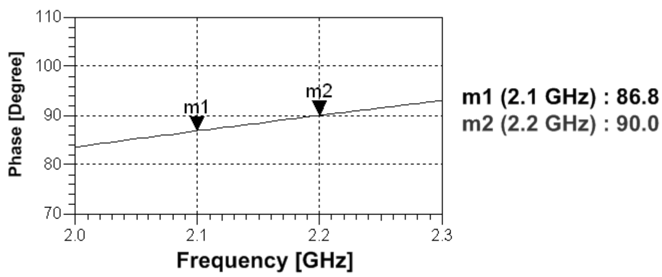


(a)

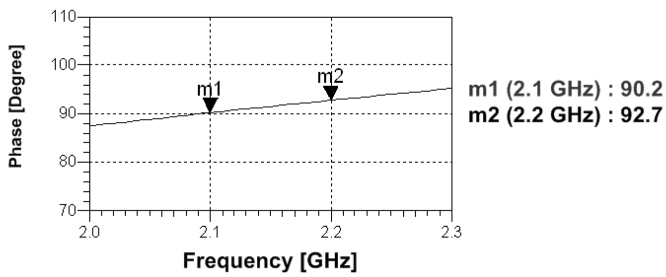


(b)

Fig. 4. Load impedance variation of the peaking amplifier (a) diode off for 2.2 GHz (b) diode on for 2.1 GHz.



(a)



(b)

Fig. 5. Output phase difference of the main and peaking amplifiers (a) diode off for 2.2 GHz (b) diode on for 2.1 GHz.

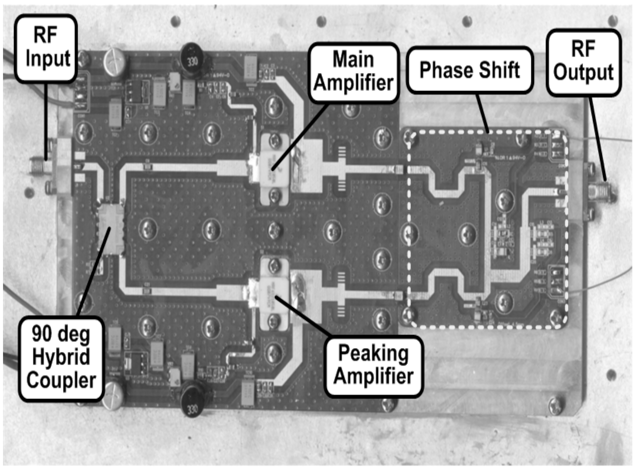


Fig. 6. Top view of the proposed Doherty amplifier.

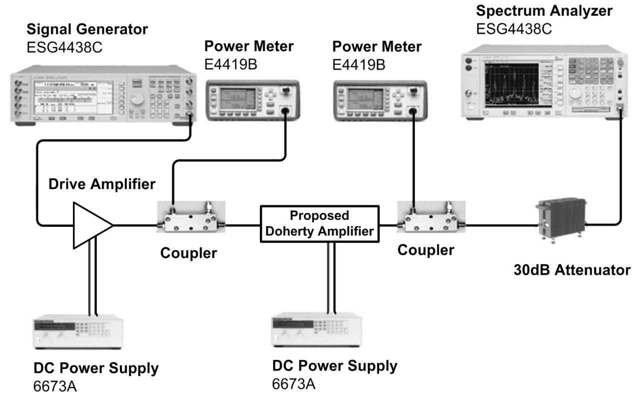
III. IMPLEMENTATION AND MEASUREMENT RESULTS

The proposed Doherty amplifier was fabricated and measured. A photograph of the proposed Doherty amplifier is shown in Fig. 6. A MOSFET device, which is MRF6S21050 by Freescale corporation is used. The MRF6S21050 has a 50 W peak envelop power and matching circuits were designed by load-pull simulation with the Agilent Advanced Design System 2008. Moreover, another two amplifiers with same device, a single Class-AB amplifier and a push-pull amplifier, were designed for comparison of performances.

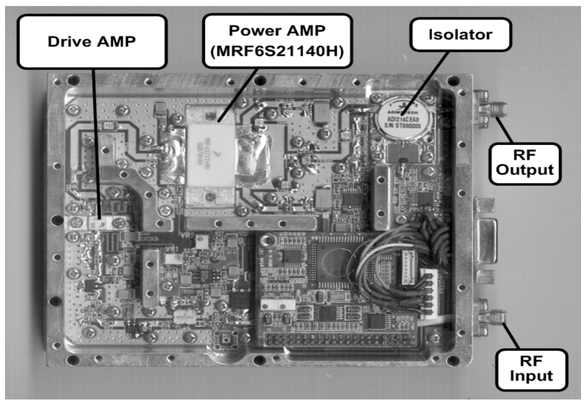
The measurement was done by using Agilent ESG4438C Signal Generator, E4440A PSA Series Spectrum Analyzer and E4419B Power Meter. Fig. 7(a) shows the test bench of the proposed PA. The class-AB amplifier with MRF6S21140 MOSFET by Freescale, which has a gain of 46 dB and a P_{1dB} of 50 dBm, was fabricated for drive amplifier as shown in Fig. 7(b).

The proposed Doherty amplifier can carry on a P_{sat} of 50 dBm and a power gain of 14.5 dB. Fig. 8 shows the gain and power-added efficiency (PAE) characteristics of the proposed Doherty amplifier with off-state diode compared with push-pull Class-AB PA for a 2.2 GHz continuous wave signal. The Doherty amplifier displays the excellent efficiency of about 50% at the 6 dB back-off power region, which is 21% higher than that of push-pull PA. On the other hand, if the diode is turned on, Doherty amplifier operate optimally at 2.1 GHz. The gain and PAE characteristics of the Doherty amplifier with on-state diode are shown in Fig. 9 and results are similar to the performances at 2.2 GHz. According to the change of the diode on-state from off-state, PAE of the Doherty amplifier is enhanced about 5% at the 6- and 8-dB back-off power region for a 2.1 GHz CW signal, respectively. Measured PAE of the Doherty amplifier according to the variation of the operating frequency is shown as Fig. 10. This result indicates that switching PIN diode is exactly operated and can control output phase of the compensation line of the Doherty amplifier at each frequency. As a result, it is possible that operating frequency is tuned by varying the capacitance of phase shifter.

Fig. 11 shows the spectrum of the proposed Doherty amplifier for 2.2 GHz modulated signal, which is 1FA of W-CDMA 64 DPCH Test Model 1 with 5 MHz bandwidth at 3 dB back-off power level from P_{sat}. Due to the saturation region, Adjacent Channel Leakage Ratio (ACLR) at 5 MHz is about 30 dBc and Error Vector Magnitude (EVM) is about 4%. Although these values are objectively deficient for linearity specification, ACLR and EVM are respectively improved 4 dBc and 1% by using phase shifter with diode at 2.1 GHz.



(a)



(b)

Fig. 7. (a) Test bench for measurement and (b) drive amplifier.

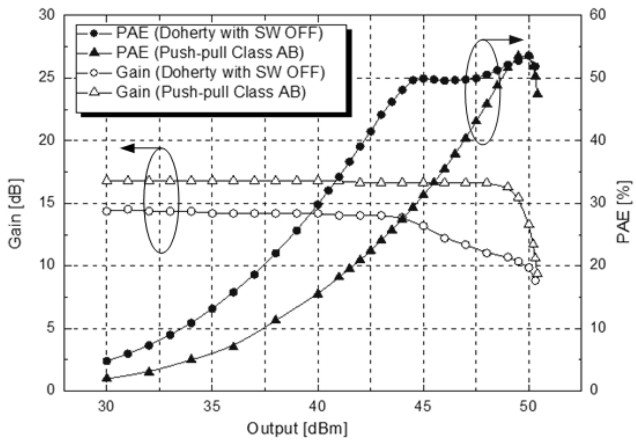


Fig. 8. Measured characteristics of the proposed PA compared with push pull amplifier at 2.2 GHz.

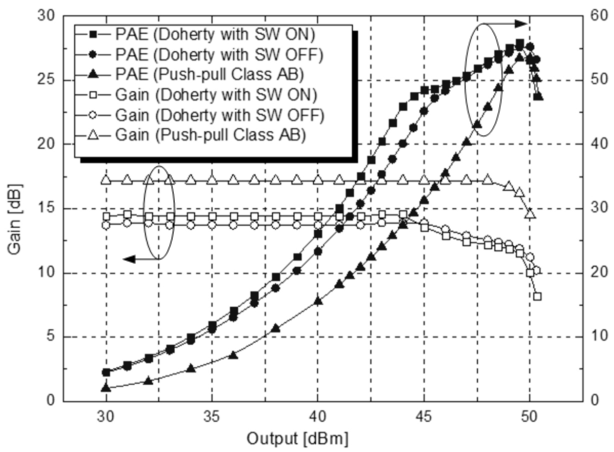


Fig. 9. Measured characteristics of the proposed PA compared with push pull amplifier at 2.1 GHz.

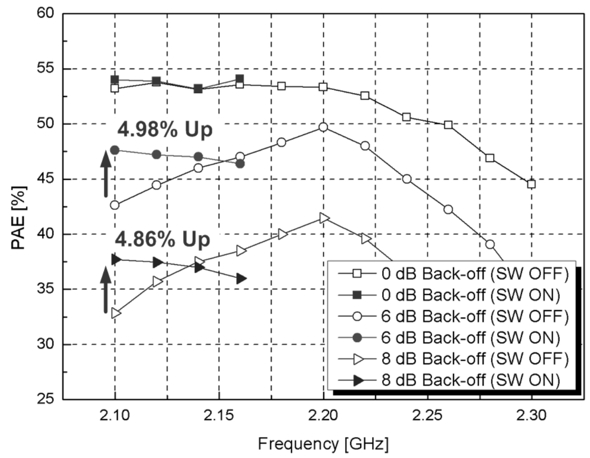


Fig. 10. Measured PAE of the Doherty amplifier according to the variation of the frequency.

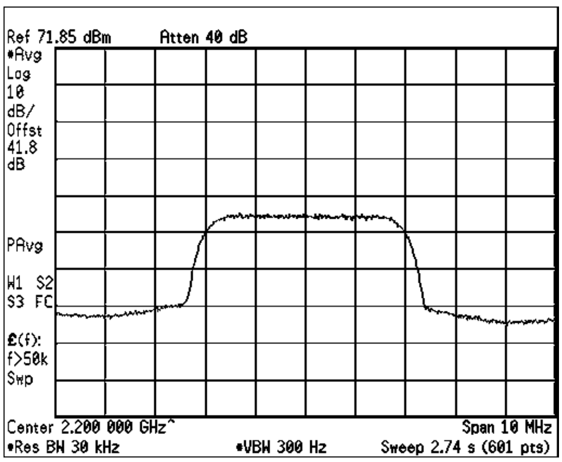


Fig. 11. Measured spectrum of the proposed Doherty amplifier for 2.2 GHz W-CDMA modulated signal at 47 dBm.

IV. CONCLUSION

A dual-band switching Doherty PA is implemented using PIN diode at the compensation line. The operating frequency of the proposed Doherty PA is tuned by the state of diode, which removes reactance component at each frequency. Due to the longer electrical length of the compensation line resulted from on-state of PIN diode, output circuit of the Doherty PA is set to 2.1 GHz from 2.2 GHz. A 4.98% of PAE is enhanced at 2.1 GHz compared with the conventional Doherty PA. The advantages of the proposed Doherty PA including dual-band and a higher PAE will be important role for multi- and broad-band communication and improved by using advanced device such as gallium nitride (GaN) transistor.

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