A Wideband Doherty-Like Architecture Using a Klopfenstein Taper for Load Modulation

Eduard Bertran, *Senior Member, IEEE*, and Mehran Yahyavi

***Abstract*—A novel Doherty-like power amplifier (DPA) has been fabricated using 15 W, 2.7 GHz, GaN HEMT transistors. The quarter-wave transformer used in the classical DPA topology is replaced by a matching network including a Klopfenstein taper. From a practical prototype realization, this modification has demonstrated that the resulting DPA bandwidth (BW) is increased in comparison with the conventional topology while keeping the efficiency figures. Moreover, this design allows an easy tuning of the group delay through the output reactance of the taper, resulting in a more straightforward adjustments than other recently-published designs where the quarter-wave transformer is replaced by multi-section transmission lines (hybrid or similar). Experimental results have shown an average efficiency of 47.2% for the HSPA+ modulation centered at 2.25 GHz.**

***Index Terms*—Doherty power amplifier (DPA), drain efficiency, fractional bandwidth, Gallium nitride (GaN), Klopfenstein taper.**

I. Introduction

RECENT multi-band communication schemes have enlarged the BW needs, being two main approaches regarding the power amplifier (PA): to employ resonant narrowband structures along the whole application band or the employment of a wideband PA [1]. Hence, for such multi-band applications, the limited BW of the Doherty PAs (DPAs) has become a drawback.

The investigations guided to increase the DPA BW may be roughly classified into two main lines: reduction of the frequency constraint of the quarter-wave line inverter [2] and solving imperfections in the output matching networks (OMN) [1], i.e., modifying their reflection coefficients. An effective approach is based on the replacement of the $\lambda/4$ impedance transformer by lumped π networks or by multi-section transmission lines [3]–[6]. Other solutions, similar to Doherty [7] and sometimes even presented as DPA [8] use a combining network which, instead to act as an inverter; it makes the load modulation by means of a transformer that matches the DPA to the optimum load at the power back-off.

The Klopfenstein taper has been experimented in DPAs [9] for matching the load, but not as an alternative to the load modulation scheme. In [10] the taper was not use to also adjust the group delay. In the line of [7] and [8], in this letter we use a combining network as impedance transformer. Here we merge multi-section transformers and a Klopfenstein taper. This combiner aims at solving the compromise between the DPA gain, PAE and BW, while providing a tool for the broadband adjustment of the main PA output reactance. This adjustment is based on the relatively easy control of the reactance at the output of the Klopfenstein taper, so allowing a good regulation of the relative group delay between branches.

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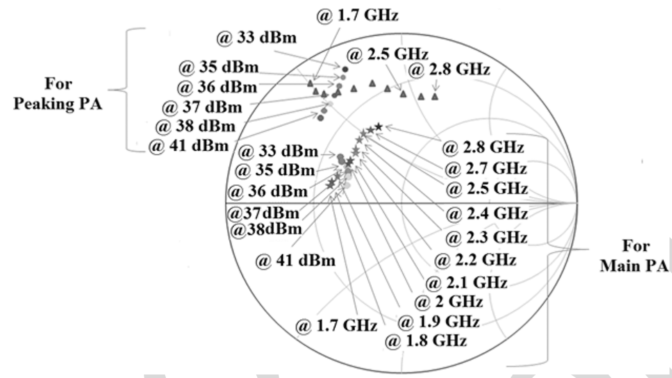

Fig. 1. Output impedances of the main PA and peaking PA for maximum power at different frequencies.

II. Design Approach

As the beginning of the design procedure, a load-pull analysis for finding the optimum impedances for the HEMT devices has been performed (Fig. 1). These devices have been 15 W gallium nitride (GaN) CGH27015F transistors from Cree, used in both the main and the peaking amplifiers. For the class AB amplifier (main amplifier), the optimal impedances (regarding the power efficiency at saturated power and at the intermediate frequency of 2 GHz) have resulted $5.5+j7.5\ \Omega$ for the input and $19+j7.2\ \Omega$ for the output.

Similarly, for the class C (peaking amplifier), the input and output impedances have been $3 + j4.5\ \Omega$ and $7.8 + j29.1\ \Omega$, respectively. In this design, the amplifiers are biased in Class AB ($V_{GS} = -2.5$ V, $V_{DS} = 28$ V) and class C ($V_{GS} = -5.5$ V, $V_{DS} = 28$ V) respectively. The substrate has been R04000. The passive biasing networks use radial stubs along with grounded bypass capacitors. Especially relevant has been the choice of the capacitors in the biasing of the class C amplifier, because in the experimentation it has been detected a risk of low-frequency oscillations. To match the aforementioned input impedances, binomial multi-section transformers have been employed. Besides, a Wilkinson divider has been used to compensate the gain reduction in the Doherty region, with power asymmetries of

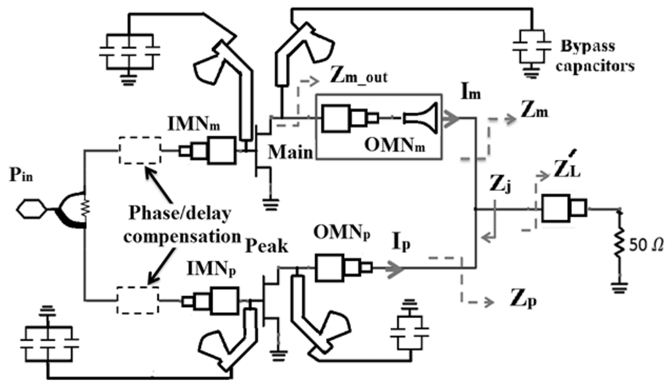

Fig. 2. Schematic of the proposed PA.

80% (20% for the main amplifier), empirically adjusted for gain flatness.

The schematic of the proposed broadband amplifier is shown in Fig. 2. It follows the general structure of [7] and [8], being our OMN made in microstrip by merging binomial transformers and a Klopfenstein taper (the last just in the OMN_m on the main amplifier). The impedance in the Z_j junction point may be calculated as usually

$$Z_m = Z_j \left(1 + \frac{I_p}{I_m}\right) \tag{1}$$

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where I_m and I_p are the drain currents of the main and the peaking amplifiers, respectively. To tune the design, there are to starting points: 1) the value of Zj should be, ideally, the same as Z'_L (25 Ω in the design) to nullify the return losses (RL), and 2) the OMN_m is split into a binomial transformer (for its BW) and a Klopfensten taper [11] that, apart from the increased BW, allows a direct control of the Z_m susceptance by adjusting the length of the taper, according to

$$\Gamma(\theta) = \Gamma_0 e^{-j\beta L} \frac{\cos\sqrt{(\beta L)^2 - A^2}}{\cosh A} \text{ for } \beta l > A \tag{3}$$

being $\Gamma(\theta)$ the reflection coefficient, and $A = \cos\mathrm{h}^{-1}((\Gamma_0)/(\Gamma_m))$, $\Gamma_0 = (1)/(2)\ln((Z_L)/(Z_0))$, where Γ_m is the maximum ripple in the passband. The cutoff frequency of the taper decreases when either the taper length increases or the value of the factor A decreases. No upper-end cutoff frequency exists (theoretically) as defined in the relationship of $\beta L > A$. The objective of the reactance adjustment is to control the OMN_m delay. As demonstrated in [7], a non-zero susceptance is preferable to a quasi-open circuit impedance (as in Doherty amplifiers) to achieve better BWs. The OMN_m is a reciprocal, loss-free two-port network

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being θ a parameter dependent of the network reactance that controls the group delay and, consequently, helps to equilibrate delays among branches.

After ADS simulations searching for the compromise among gain, PAE and BW, with priority to the last feature; the tuned value of Z_j has been 22.68–j7.34 Ω (at 2.25 GHz) The similarity of this value to the optimal Z_{m_out} may invite to match them directly, but in this case the filter parameters become too sensitive. In particular, the PAE results too sensitive to small tolerances in the design of such matching network (PAE drops by 10–15%).

Therefore, we have constructed the OMN_m by combining a multi-section transformer and a Klopfenstein taper. The multi-section transforms the optimal Z_{m_out} of the transistor to 85 Ω, a value obtained from an optimization process aiming at the minimization of the RL in the center of the band (2.25 GHz), and the taper moves this impedance to produce the aforementioned value of $Z_j = 22.68 - j7.34$ Ω at saturation (Z_m in parallel with $Z_p = 48$ Ω). At power back-off, $Z_p \to \infty$, so the value of $Z_m = Z_j$ becomes 36-j24.4 Ω. According to (3), adjusting the reactance is as easy as to change the length of the taper or, alternatively, to allow different ripples in the passband. Our design has been made for$\Gamma_m = 0.01$. I.e. for a taper of 37 mm to allow the double in the ripple figure reduce the reactance to the half. In Fig. 3 it is shown the prototype.

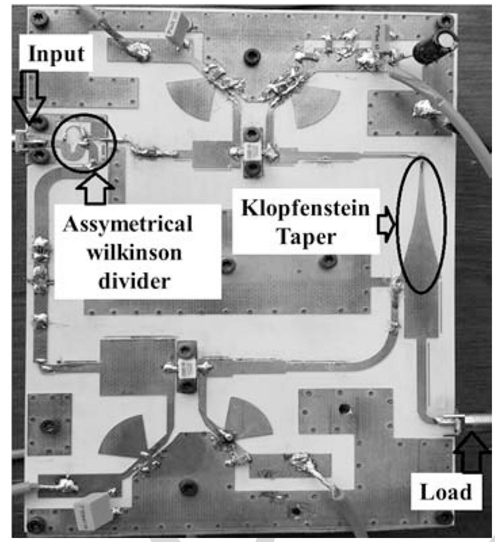

Fig. 3. Photograph of the implemented prototype of the DPA.

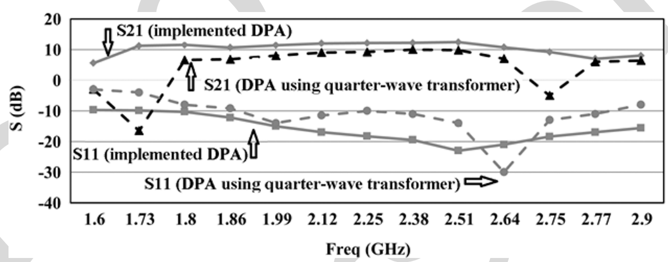

Fig. 4. Measured S-parameters of the proposed amplifier, compared with a conventional DPA (some schematic, but with the classical $\lambda/4$ transformer).

III. Experimental Results

As depicted in Fig. 4, the scattering parameters of the proposed DPA indicate a bandwidth operation from 1.7 to 2.75 GHz (47% of fractional bandwidth).

The power gain and the drain efficiency (DE) versus input power for 3 selected frequencies along the band are presented in Fig. 5. DE ranges from 37% to 48% in a 6 dB output back-off

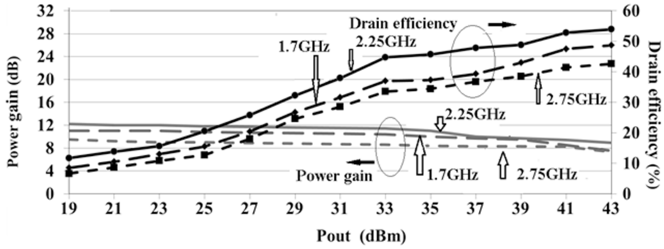

Fig. 5. Measured drain efficiency and power gain versus output power (Pout).

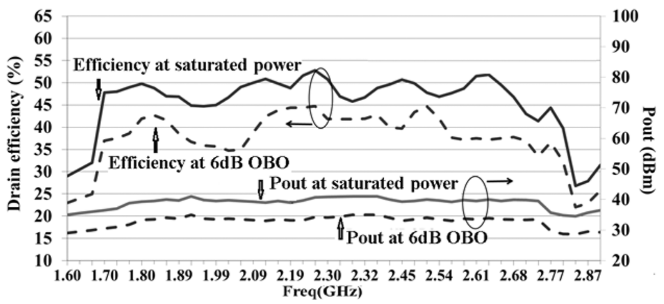

Fig. 6. Measured power out and DE (at 6 dB OBO and at saturated power).

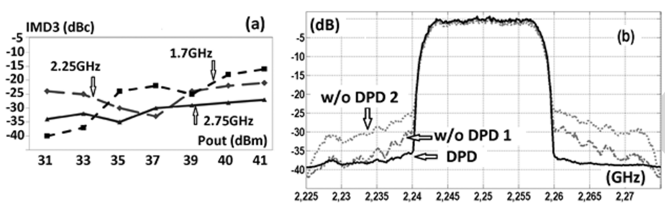

Fig. 7. (a) IMD3 measured at 3 different frequencies and (b) output spectrum with a 20-MHz WCDMA (HSPA+ expanded, release 10) driving signal, at center frequency of 2.25 GHz and average output power of 33 dBm (w/o DPD1) and 36 dBm (w/o DPD2). Common benefits to apply a memory polynomial DPD (ACPR increased in 10–15 dB) are indicated in the figure.

(OBO) operation. DE at saturated output power ranges from 43% at 2.75 GHz to 54% at 2.25 GHz.

Fig. 6 illustrates some measurements of the output power. They have been carried out at input power levels of 26 dBm (6 dB OBO and 32 dBm (saturated output power). In addition, the DE measurements at the same power levels are also reported.

The third-order inter-modulation distortion (IMD3) for different power levels of the proposed DPA is depicted in Fig. 7. These IMD3 measurements, showing the usual order of magnitude in other DPAs, are based on two-tone signals with 1 MHz frequency offset, around three different frequencies of 1.7, 2.25, and 2.75 GHz. In the center frequency of 2.25 GHz, the IMD3 figure ranges from −25 dBc to −35 dBc in the Doherty region. From the two-tone tests, no relevant memory effects have been detected (i.e., no visible IMD asymmetry) for tone separations up to 200 MHz (approximately, 20% of the BW). With a HSPA+ expanded to 20 MHz (Release 10) the ACPR results of 34.2 dB (at 9 dB OBO) and 27 dB (at 6 dB OBO). For the HSPA+ modulation (centered at 2.25 GHz) the average efficiency is 47.2%.

What is compared in Table I is the performance of the fabricated wideband DPA with some previous works.

IV. Conclusion

A novel architecture for a wideband DPA has been presented. It is based on the replacement of the classical quarter-wave impedance inverter by a hybrid network including a Klopfenstein taper which facilitates the adjustment of the group delay. According to the results concerning the peak output power, the drain efficiency, the bandwidth and the linearity performance, the resulting DPA shows similar figures compared with alternative solutions recently presented, with the merit of showing a straightforward design adjustment. In particular, the fabricated DPA presents a 47% of fractional bandwidth with an average efficiency higher than 47% for an HSPA+ signal.

TABLE I
Comparison With Other Wideband DPAs

	Freq. (GHz)	BW (%)	DE (%)	Gain (dB)	Max. Pout (dBm)	IMD3 @ SAT dBc
[3]	1.7 - 2.4	36.3	43 - 59 (6 dB OBO) 53 – 72 (@ SAT)	9.4 - 10	42	-
[4]	1.5 – 2.5	50	> 49 (6 dB OBO and SAT)	4.2 - 11	42	-
[5]	1.05 – 2.55	83.3	35 - 58 (6 dB OBO) 45 – 83 (@ SAT)	9 – 12.5	40 - 42	-
[6]	6.8 – 8.5	22	39 - 42 (6 dB OBO) 45 – 55 (@ SAT)	6 - 13.5	35	-
[7]	1.96 – 2.46	23	> 40 (6 dB OBO)	7 – 15	40 – 41	14
[8]	0.8 - 1.2	40	30.3 - 40.1 (6 dB OBO) 50.8 - 78.5 @ SAT	10.8 - 14.8	40.2 - 42.9	16
[9]	0.7 - 1	35.3	50 - 60.6 (6 dB OBO) 65 - 67.3 @ SAT	14.5 - 23.5	49.9	-
TW	1.7 - 2.75	47	37 - 48 (6 dB OBO) 43 – 54 (@ SAT)	8.5 - 11	42	18

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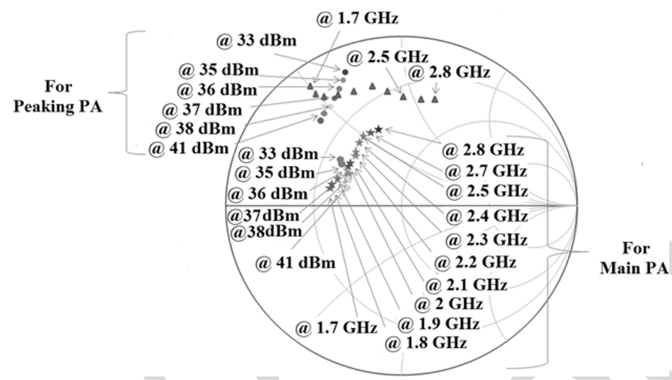

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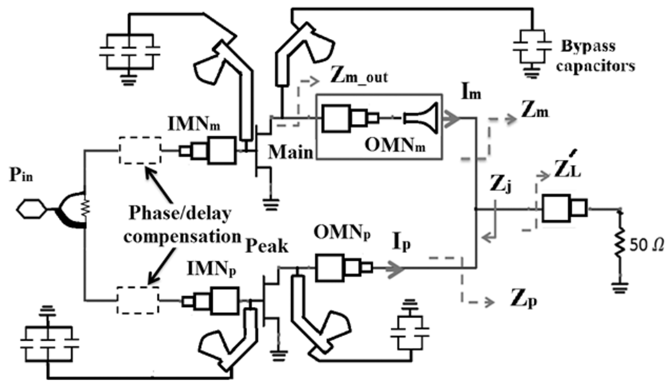

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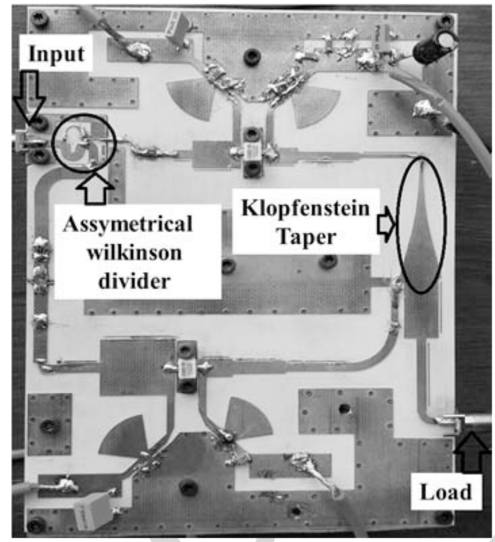

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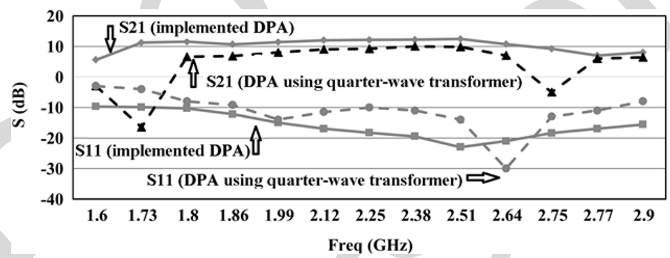

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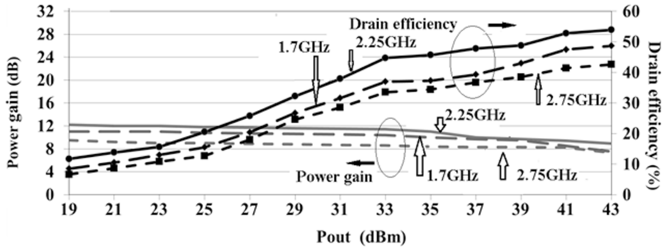

Fig. 5. Measured drain efficiency and power gain versus output power (Pout).

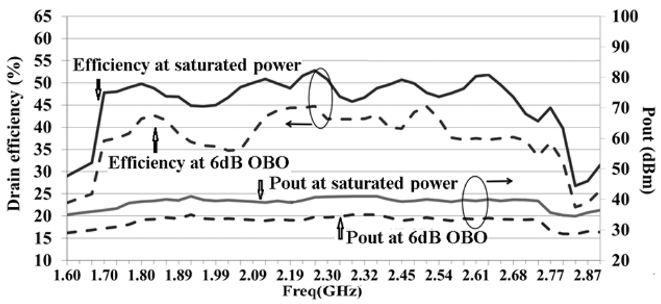

Fig. 6. Measured power out and DE (at 6 dB OBO and at saturated power).

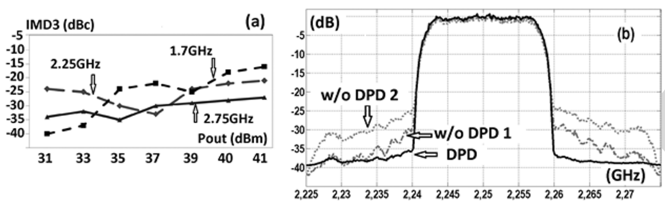

Fig. 7. (a) IMD3 measured at 3 different frequencies and (b) output spectrum with a 20-MHz WCDMA (HSPA+ expanded, release 10) driving signal, at center frequency of 2.25 GHz and average output power of 33 dBm (w/o DPD1) and 36 dBm (w/o DPD2). Common benefits to apply a memory polynomial DPD (ACPR increased in 10–15 dB) are indicated in the figure.

(OBO) operation. DE at saturated output power ranges from 43% at 2.75 GHz to 54% at 2.25 GHz.

Fig. 6 illustrates some measurements of the output power. They have been carried out at input power levels of 26 dBm (6 dB OBO and 32 dBm (saturated output power). In addition, the DE measurements at the same power levels are also reported.

The third-order inter-modulation distortion (IMD3) for different power levels of the proposed DPA is depicted in Fig. 7. These IMD3 measurements, showing the usual order of magnitude in other DPAs, are based on two-tone signals with 1 MHz frequency offset, around three different frequencies of 1.7, 2.25, and 2.75 GHz. In the center frequency of 2.25 GHz, the IMD3 figure ranges from -25 dBc to -35 dBc in the Doherty region. From the two-tone tests, no relevant memory effects have been detected (i.e., no visible IMD asymmetry) for tone separations up to 200 MHz (approximately, 20% of the BW). With a HSPA+ expanded to 20 MHz (Release 10) the ACPR results of 34.2 dB (at 9 dB OBO) and 27 dB (at 6 dB OBO). For the HSPA+ modulation (centered at 2.25 GHz) the average efficiency is 47.2%.

What is compared in Table I is the performance of the fabricated wideband DPA with some previous works.

IV. Conclusion

A novel architecture for a wideband DPA has been presented. It is based on the replacement of the classical quarter-wave impedance inverter by a hybrid network including a Klopfenstein taper which facilitates the adjustment of the group delay. According to the results concerning the peak output power, the drain efficiency, the bandwidth and the linearity performance, the resulting DPA shows similar figures compared with alternative solutions recently presented, with the merit of showing a straightforward design adjustment. In particular, the fabricated DPA presents a 47% of fractional bandwidth with an average efficiency higher than 47% for an HSPA+ signal.

TABLE I
Comparison With Other Wideband DPAs

	Freq. (GHz)	BW (%)	DE (%)	Gain (dB)	Max. Pout (dBm)	IMD3 @ SAT dBc
[3]	1.7 - 2.4	36.3	43 - 59 (6 dB OBO) 53 – 72 (@ SAT)	9.4 - 10	42	-
[4]	1.5 – 2.5	50	> 49 (6 dB OBO and SAT)	4.2 - 11	42	-
[5]	1.05 – 2.55	83.3	35 - 58 (6 dB OBO) 45 – 83 (@ SAT)	9 – 12.5	40 - 42	-
[6]	6.8 – 8.5	22	39 - 42 (6 dB OBO) 45 – 55 (@ SAT)	6 - 13.5	35	-
[7]	1.96 – 2.46	23	> 40 (6 dB OBO)	7 – 15	40 – 41	14
[8]	0.8 - 1.2	40	30.3 - 40.1 (6 dB OBO) 50.8 - 78.5 @ SAT	10.8 - 14.8	40.2 - 42.9	16
[9]	0.7 - 1	35.3	50 - 60.6 (6 dB OBO) 65 - 67.3 @ SAT	14.5 - 23.5	49.9	-
TW	1.7 - 2.75	47	37 - 48 (6 dB OBO) 43 – 54 (@ SAT)	8.5 - 11	42	18

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