Test Report: PMP41068

Discrete Single-Ended Class D Power Stage Reference Design With GaN HEMT

Description

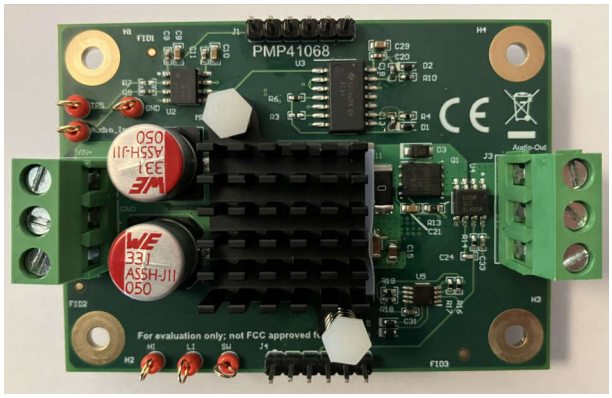
This reference design describes a discrete, single-ended, class D power stage with GaN high electron mobility transistors (HEMT). This design uses the LMG2100R044 as power switches to make a class D audio amplifier working at MHz frequency and makes a contrast with the one working at kHz frequency. This GaN-based class D power stage shows excellent efficiency at both MHz and kHz.

Features

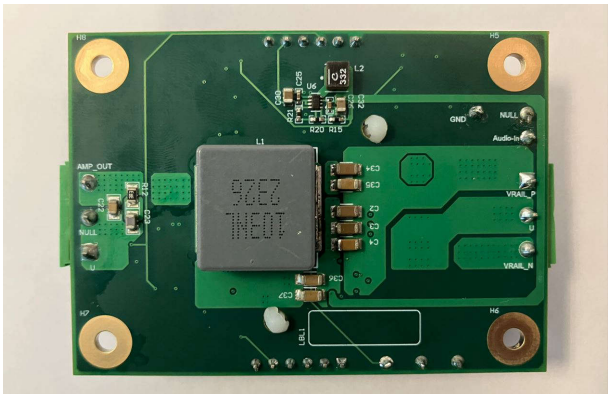
- GaN-based MHz single-ended class D power stage
- LMG2100R044 available as power switch for class D amplifier
- Excellent efficiency for both MHz and kHz class D applications

Applications

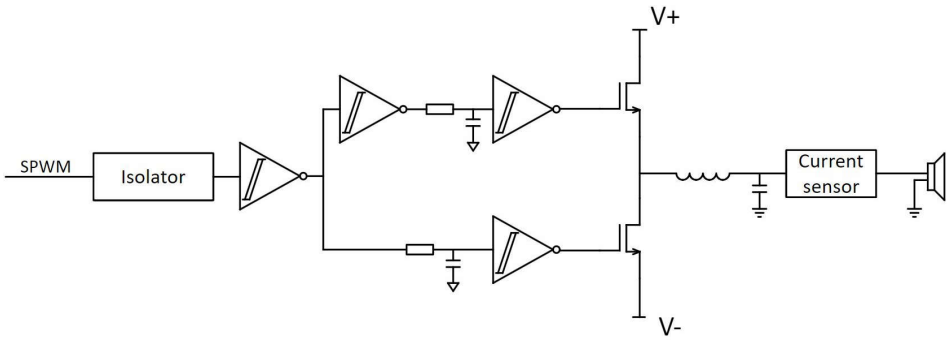
- Automotive external amplifier



Top View



Bottom View



Block Diagram

1 Test Prerequisites

This chapter describes the functional parameters of class D power stage and the required test equipment.

1.1 Voltage and Current Requirements

Table 1-1. Voltage and Resistance Requirements

Parameter	Specifications
Input Voltage	10 Vdc to 60 Vdc
Switching Frequency	1 MHz, 2 MHz, 384 kHz
Sine-wave Frequency	1 kHz, 100 Hz, 10 kHz
Output Resistor	4 Ω

1.2 Required Equipment

- DC Source: Chroma 62006P-100-50
- DC Source: GW Instek GPS-3303C
- Multimeter: Fluke 287C
- Audio Analyzer: APx500 Series
- Oscilloscope: Tektronix DPO3054
- Electrical thermography: Fluke TiS55
- Arbitrary Waveform Generator: AFG3522
- Resistor Load: RXG24-800W-4RF

1.3 Considerations

Considering that the class D power stage needs a sinusoidal pulse width modulation (SPWM) signal, the TLV3601 device was used to build a comparator circuit. Pin 3 of TLV3601 was connected to AFG3522, which generates a triangle waveform. Pin 4 of TLV3601 was connected to APx500, which generates a sinusoidal waveform, thus producing a SPWM waveform.

The amplitude modulation ratio of SPWM is defined as the V_{PP} of the sine wave over V_{PP} of the triangle wave. The amplitude modulation ratio is set to 0.73 in the test results in this report, if not indicated otherwise.

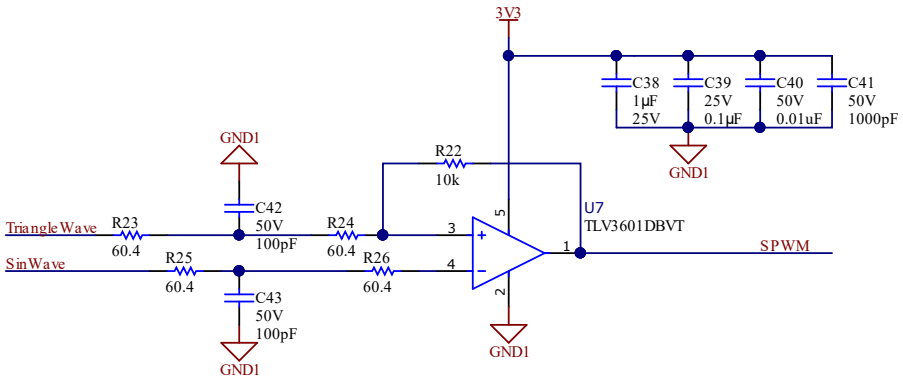


Figure 1-1. TLV3601 Circuit

1.4 Dimensions

The board dimensions are 71 mm (length) × 51 mm (width) × 10 mm (height).

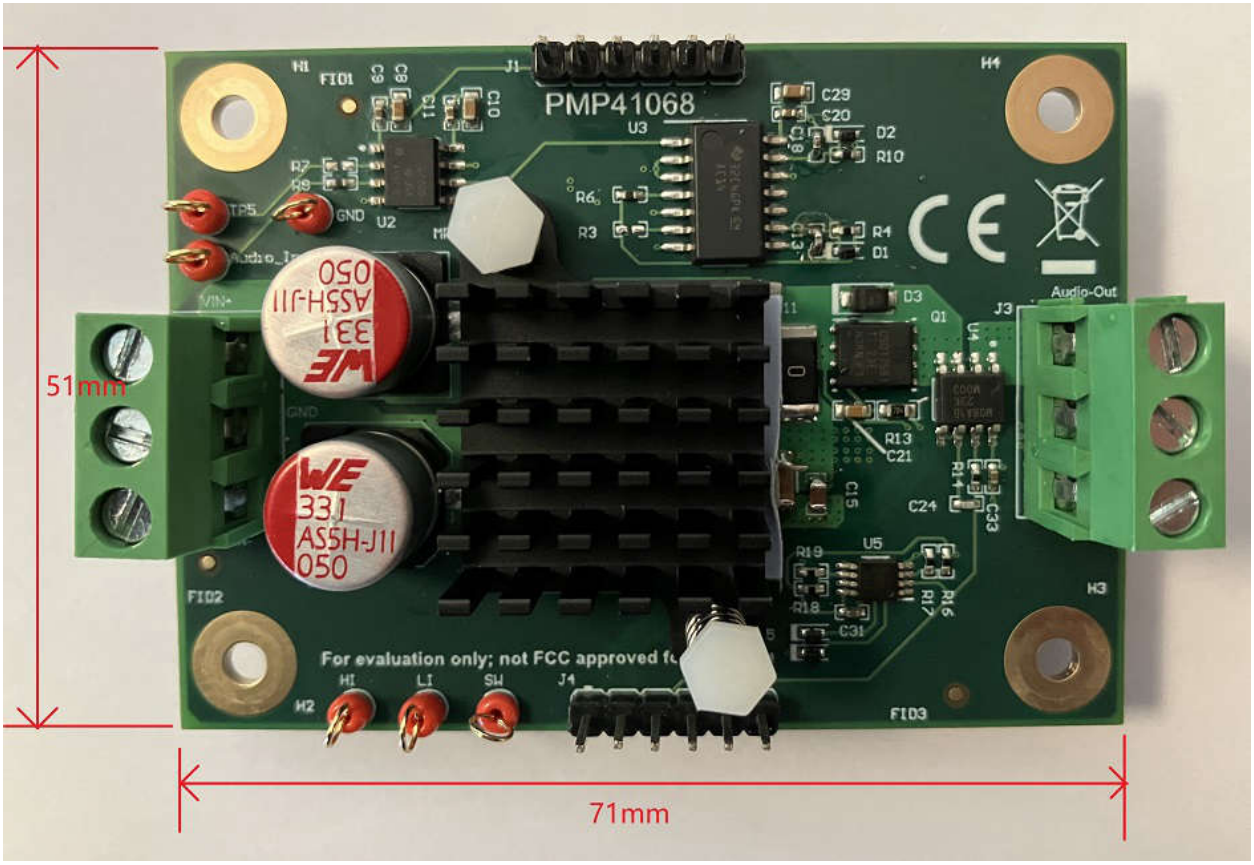


Figure 1-2. Board Dimensions

2 Testing and Results

The class D power stage is configured as open loop, so only efficiency, thermal images, and idle power loss are tested.

2.1 Efficiency Graphs

Efficiency is shown in the following figures.

The test conditions for the results in Figure 2-1 through Figure 2-5 use a 4-Ω resistor, with heat sink, and no airflow.

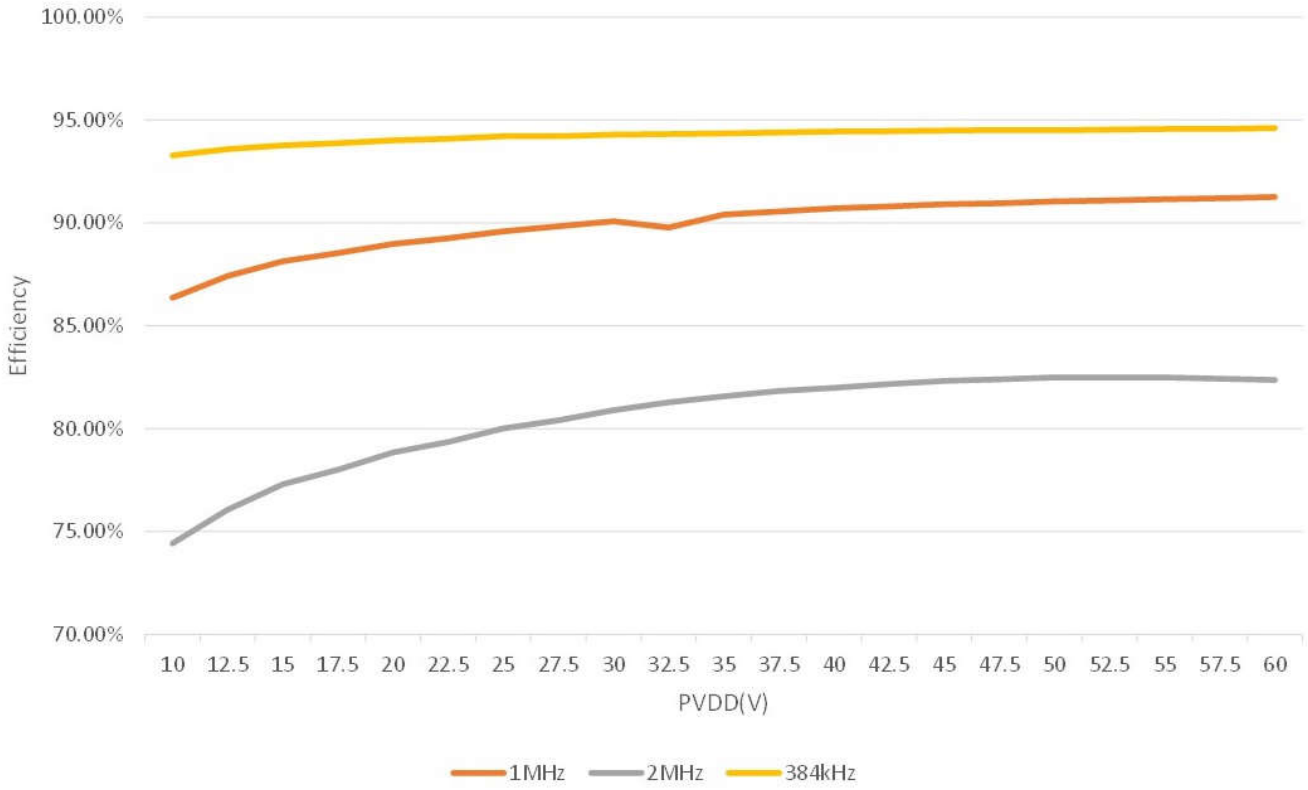


Figure 2-1. Efficiency Graph With 1-kHz Sine-Wave Frequency and 0.73 Amplitude Modulation Ratio

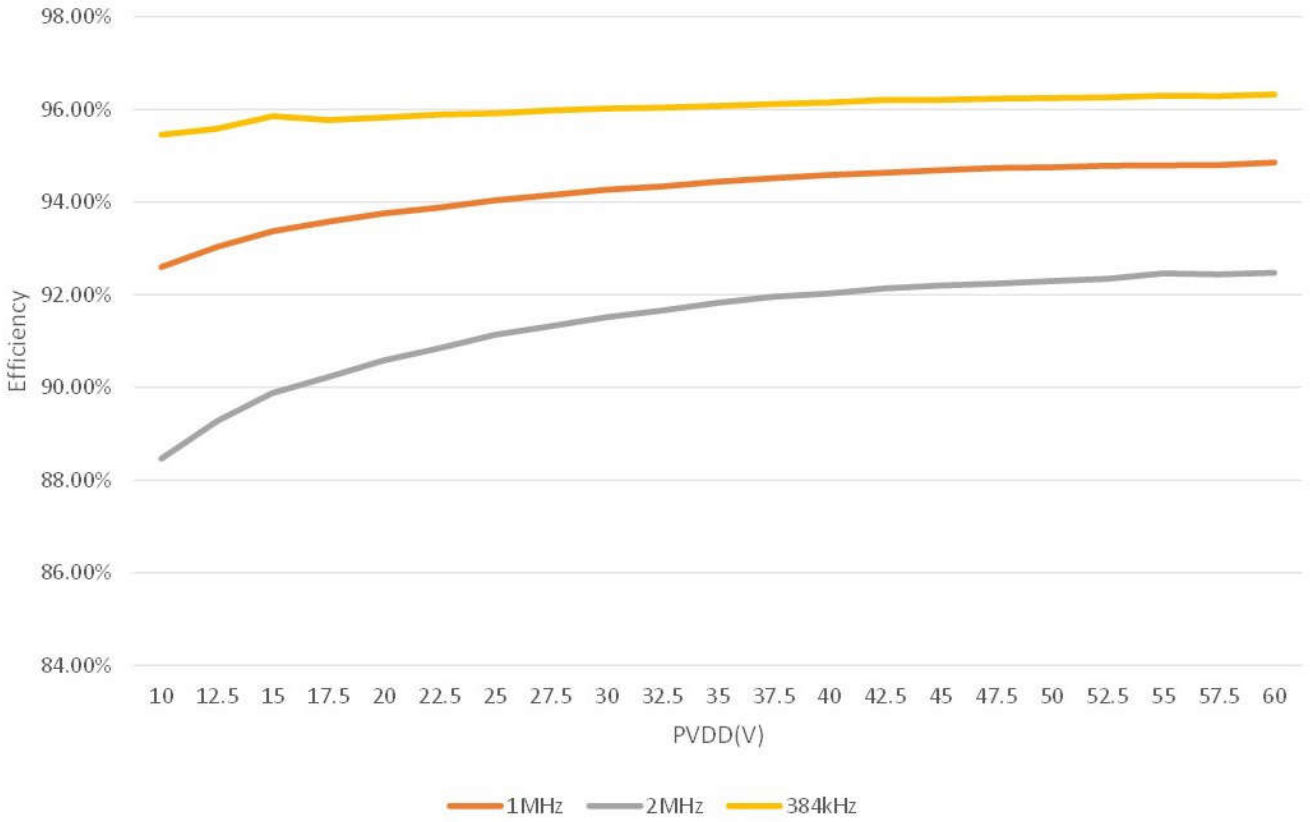


Figure 2-2. Efficiency Graph With 1-kHz Sine-Wave Frequency and 1.0 Amplitude Modulation Ratio

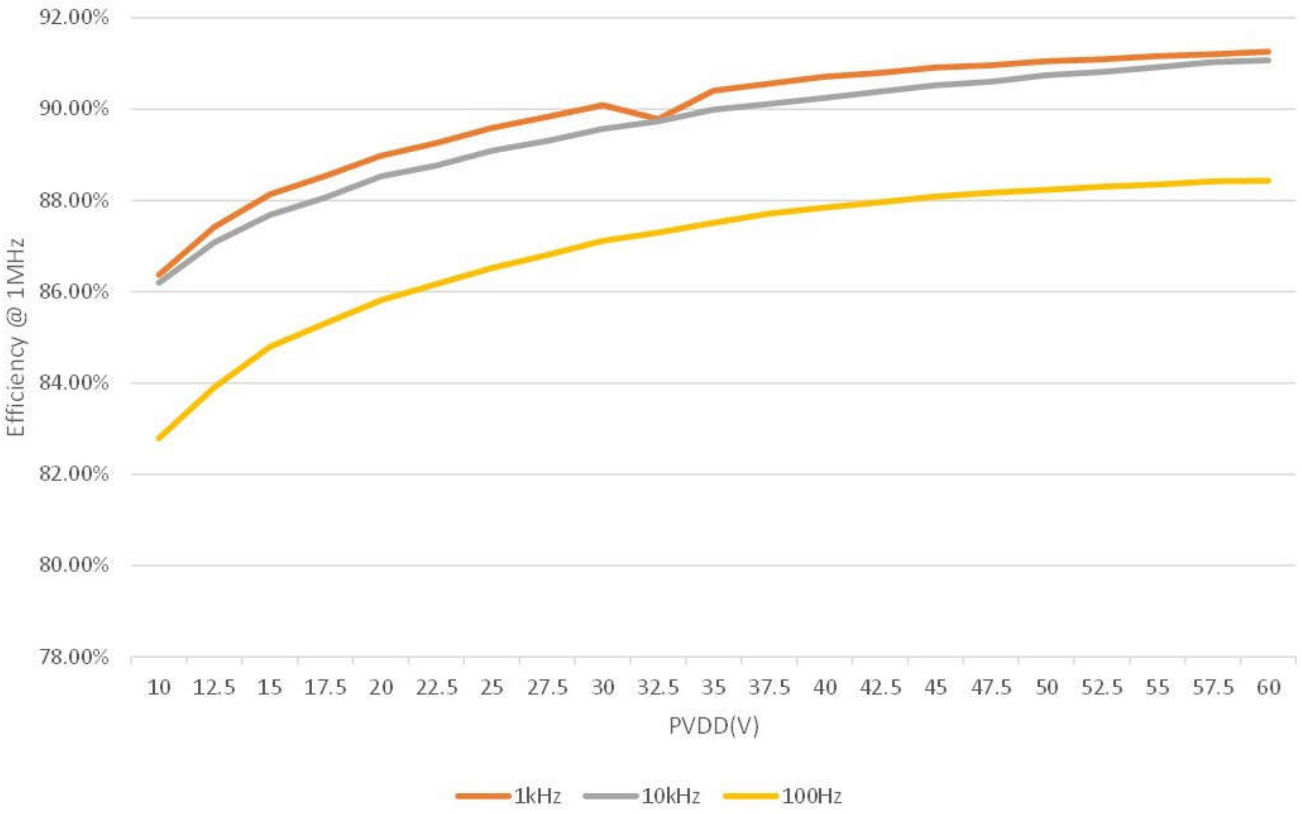


Figure 2-3. Efficiency Graph With 1-MHz Switching Frequency and 0.73 Amplitude Modulation Ratio

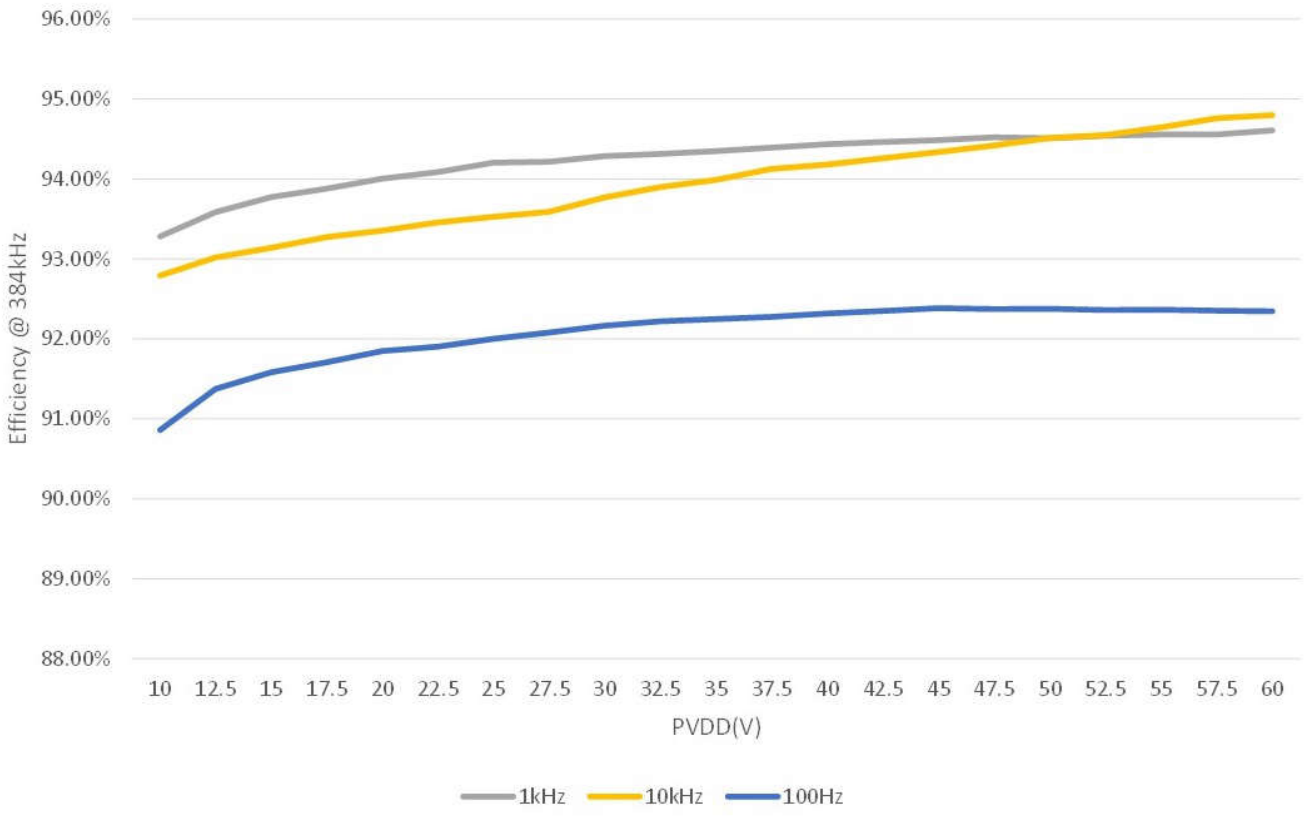


Figure 2-4. Efficiency Graph With 384-kHz Switching Frequency and 0.73 Amplitude Modulation Ratio

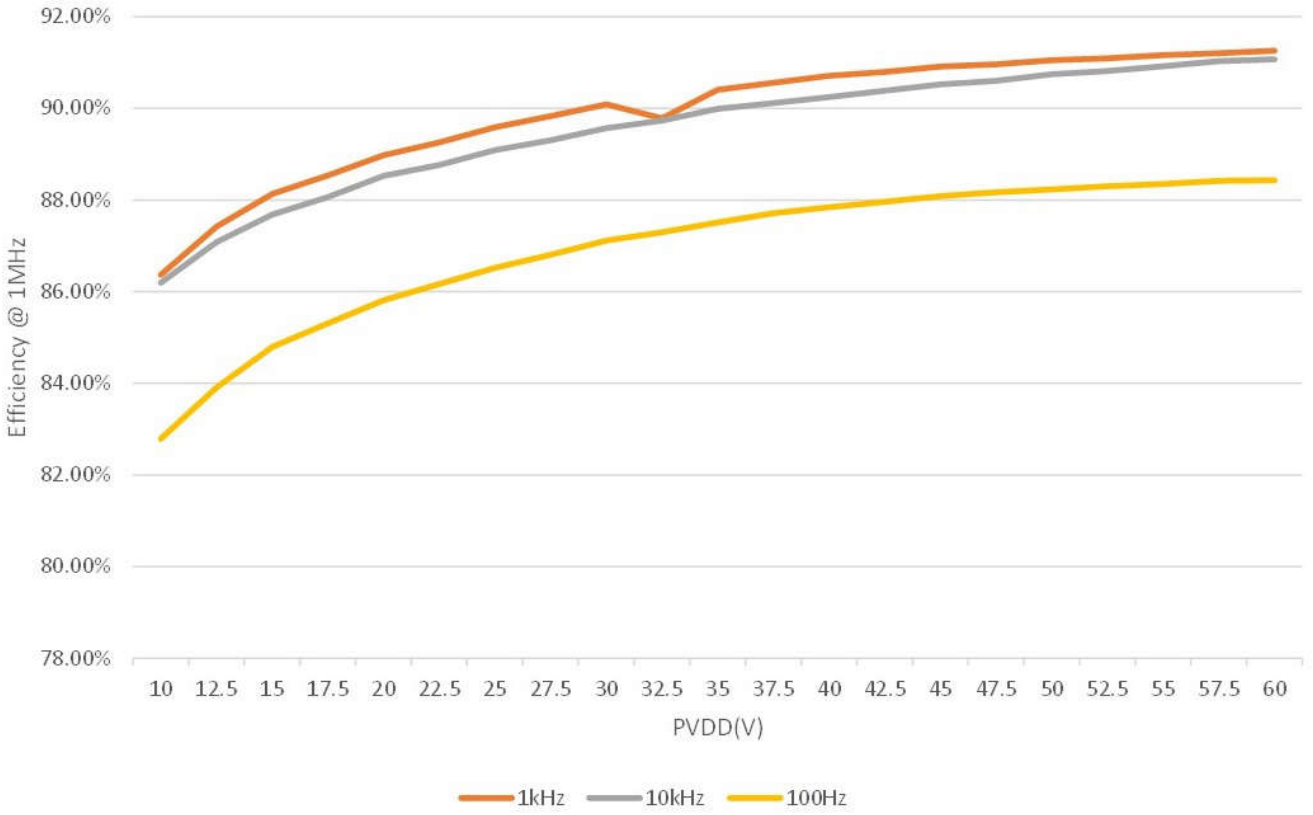


Figure 2-5. Efficiency Graph With 2-MHz Switching Frequency and 0.73 Amplitude Modulation Ratio

2.2 Efficiency Data

Table 2-1 shows the efficiency data for Figure 2-1.

Table 2-1. Efficiency Data With 1-kHz Sine-Wave Frequency and 0.73 Amplitude Modulation Ratio

Switching Frequency	V_{IN} (Vdc)	I_{IN} (A)	Vout_rms (Vac)	I_{OUT} (A)	P_{IN} (W)	P_{OUT} (W)	Ploss(W)	Efficiency
1 MHz	9.851	0.153	2.303	0.565	1.505	1.300	0.205	86.37%
	12.644	0.193	2.952	0.724	2.444	2.137	0.307	87.42%
	15.436	0.233	3.598	0.883	3.603	3.175	0.428	88.13%
	17.534	0.263	4.082	1.001	4.617	4.087	0.529	88.53%
	20.329	0.303	4.725	1.159	6.156	5.477	0.678	88.98%
	22.427	0.332	5.207	1.277	7.452	6.651	0.801	89.25%
	25.222	0.371	5.848	1.435	9.365	8.390	0.975	89.58%
	27.320	0.400	6.329	1.552	10.936	9.824	1.112	89.83%
	30.116	0.439	6.969	1.709	13.221	11.910	1.311	90.08%
	32.217	0.470	7.450	1.826	15.155	13.606	1.549	89.78%
	35.015	0.507	8.091	1.983	17.746	16.043	1.703	90.40%
	37.815	0.546	8.733	2.139	20.628	18.680	1.948	90.56%
	40.616	0.584	9.376	2.295	23.724	21.519	2.205	90.71%
	42.715	0.613	9.858	2.411	26.180	23.770	2.410	90.79%
	45.514	0.651	10.500	2.567	29.643	26.949	2.694	90.91%
	47.615	0.680	10.981	2.682	32.383	29.454	2.929	90.96%
	50.413	0.718	11.621	2.836	36.202	32.959	3.242	91.04%
	52.512	0.747	12.100	2.951	39.205	35.712	3.494	91.09%
	55.310	0.785	12.739	3.105	43.391	39.553	3.837	91.16%
	57.410	0.813	13.217	3.220	46.657	42.552	4.105	91.20%
	60.210	0.850	13.855	3.372	51.197	46.719	4.478	91.25%
2 MHz	9.857	0.151	2.126	0.521	1.488	1.108	0.381	74.43%
	12.652	0.187	2.709	0.664	2.366	1.800	0.566	76.06%
	15.448	0.222	3.290	0.807	3.434	2.654	0.780	77.29%
	17.545	0.248	3.722	0.913	4.356	3.399	0.958	78.01%
	20.343	0.282	4.297	1.054	5.745	4.530	1.215	78.85%
	22.440	0.308	4.727	1.160	6.907	5.481	1.426	79.36%
	25.238	0.341	5.298	1.299	8.604	6.884	1.719	80.02%
	27.336	0.366	5.724	1.404	9.994	8.036	1.958	80.41%
	30.132	0.398	6.293	1.543	12.005	9.711	2.293	80.90%
	32.930	0.431	6.861	1.682	14.199	11.541	2.659	81.28%
	35.027	0.456	7.287	1.787	15.962	13.020	2.942	81.57%
	37.825	0.489	7.856	1.925	18.481	15.123	3.358	81.83%
	39.924	0.514	8.284	2.029	20.505	16.810	3.695	81.98%
	42.721	0.547	8.855	2.168	23.360	19.195	4.165	82.17%
	45.521	0.580	9.422	2.305	26.389	21.721	4.667	82.31%

Table 2-1. Efficiency Data With 1-kHz Sine-Wave Frequency and 0.73 Amplitude Modulation Ratio (continued)

Switching Frequency	V_{IN} (Vdc)	I_{IN} (A)	Vout_rms (Vac)	I_{OUT} (A)	P_{IN} (W)	P_{OUT} (W)	Ploss(W)	Efficiency
2 MHz	47.622	0.604	9.845	2.408	28.768	23.703	5.066	82.39%
	50.421	0.637	10.408	2.544	32.098	26.476	5.622	82.48%
	52.522	0.661	10.827	2.644	34.707	28.631	6.076	82.49%
	55.330	0.693	11.382	2.778	38.327	31.616	6.711	82.49%
	57.430	0.716	11.788	2.875	41.108	33.888	7.220	82.44%
	60.230	0.746	12.319	3.002	44.907	36.987	7.921	82.36%
384 kHz	9.848	0.159	2.443	0.599	1.569	1.463	0.105	93.28%
	12.639	0.204	3.134	0.769	2.575	2.409	0.165	93.59%
	15.432	0.248	3.826	0.938	3.829	3.590	0.238	93.77%
	17.527	0.281	4.344	1.066	4.930	4.629	0.302	93.88%
	20.320	0.326	5.035	1.235	6.614	6.218	0.396	94.01%
	22.416	0.359	5.553	1.362	8.038	7.563	0.475	94.09%
	25.211	0.403	6.245	1.532	10.152	9.564	0.588	94.21%
	27.311	0.436	6.763	1.658	11.902	11.214	0.688	94.22%
	30.105	0.480	7.454	1.827	14.441	13.616	0.825	94.29%
	32.904	0.524	8.144	1.995	17.229	16.249	0.980	94.31%
	35.005	0.557	8.664	2.122	19.484	18.382	1.101	94.35%
	37.803	0.601	9.357	2.290	22.701	21.428	1.273	94.39%
	39.900	0.633	9.877	2.416	25.269	23.863	1.406	94.44%
	42.697	0.677	10.570	2.584	28.910	27.310	1.600	94.46%
	45.495	0.721	11.265	2.751	32.797	30.989	1.808	94.49%
	47.596	0.754	11.786	2.876	35.864	33.899	1.965	94.52%
	50.395	0.797	12.479	3.043	40.175	37.969	2.206	94.51%
	52.494	0.830	13.000	3.167	43.554	41.176	2.378	94.54%
	55.290	0.873	13.694	3.333	48.274	45.646	2.627	94.56%
	57.400	0.906	14.216	3.458	51.993	49.163	2.830	94.56%
	60.190	0.949	14.911	3.625	57.132	54.052	3.080	94.61%

Table 2-2 show the efficiency data for Figure 2-2.

Table 2-2. Efficiency Data With 1-kHz Sine-Wave Frequency and 1.0 Amplitude Modulation Ratio

Switching Frequency	V_{IN} (Vdc)	I_{IN} (A)	Vout_rms (Vac)	I_{OUT} (A)	P_{IN} (W)	P_{OUT} (W)	Ploss (W)	Efficiency
1 MHz	9.859	0.293	3.300	0.810	2.888	2.674	0.214	92.60%
	12.654	0.374	4.233	1.040	4.730	4.401	0.329	93.04%
	15.450	0.454	5.165	1.269	7.017	6.552	0.465	93.37%
	17.546	0.515	5.865	1.440	9.027	8.448	0.579	93.58%
	20.341	0.595	6.795	1.669	12.093	11.337	0.755	93.75%
	22.439	0.654	7.492	1.839	14.677	13.779	0.898	93.88%
	25.235	0.733	8.421	2.066	18.502	17.399	1.103	94.04%
	27.331	0.792	9.119	2.236	21.657	20.391	1.266	94.15%
	30.126	0.871	10.049	2.462	26.246	24.741	1.505	94.27%
	32.223	0.930	10.746	2.631	29.967	28.270	1.698	94.33%
	35.018	1.009	11.678	2.856	35.316	33.351	1.964	94.44%
	37.814	1.087	12.611	3.081	41.104	38.851	2.253	94.52%
	39.909	1.146	13.311	3.249	45.720	43.243	2.476	94.58%
	42.704	1.224	14.242	3.473	52.261	49.457	2.804	94.63%
	45.498	1.302	15.175	3.695	59.225	56.078	3.147	94.69%
	47.594	1.360	15.874	3.862	64.718	61.310	3.408	94.73%
	50.388	1.438	16.803	4.085	72.438	68.635	3.803	94.75%
	52.480	1.495	17.500	4.250	78.473	74.379	4.095	94.78%
	55.270	1.572	18.426	4.470	86.890	82.364	4.526	94.79%
	57.340	1.628	19.111	4.632	93.372	88.515	4.858	94.80%
	60.140	1.705	20.045	4.853	102.557	97.278	5.278	94.85%
2 MHz	9.854	0.297	3.246	0.797	2.923	2.585	0.337	88.46%
	12.651	0.376	4.159	1.021	4.757	4.247	0.510	89.28%
	15.444	0.455	5.071	1.245	7.022	6.312	0.711	89.88%
	17.541	0.514	5.754	1.412	9.007	8.127	0.880	90.23%
	20.336	0.591	6.661	1.635	12.021	10.889	1.132	90.58%
	22.432	0.649	7.340	1.801	14.549	13.218	1.332	90.85%
	25.228	0.725	8.246	2.022	18.293	16.671	1.622	91.13%
	27.325	0.782	8.925	2.187	21.371	19.517	1.854	91.33%
	30.119	0.858	9.830	2.407	25.848	23.656	2.192	91.52%
	32.215	0.915	10.509	2.571	29.474	27.017	2.457	91.66%
	35.012	0.991	11.416	2.790	34.683	31.847	2.836	91.82%
	37.809	1.066	12.323	3.008	40.316	37.073	3.243	91.96%
	39.906	1.123	13.002	3.172	44.810	41.237	3.573	92.03%
	42.699	1.198	13.907	3.389	51.153	47.131	4.023	92.14%
	45.495	1.273	14.810	3.605	57.906	53.390	4.516	92.20%
	47.586	1.329	15.487	3.766	63.232	58.324	4.908	92.24%
	50.359	1.402	16.378	3.978	70.588	65.152	5.437	92.30%

Table 2-2. Efficiency Data With 1-kHz Sine-Wave Frequency and 1.0 Amplitude Modulation Ratio (continued)

Switching Frequency	V_{IN} (Vdc)	I_{IN} (A)	Vout_rms (Vac)	I_{OUT} (A)	P_{IN} (W)	P_{OUT} (W)	Ploss (W)	Efficiency
2 MHz	52.450	1.457	17.052	4.137	76.393	70.546	5.848	92.35%
	55.260	1.531	17.966	4.354	84.609	78.231	6.377	92.46%
	57.380	1.590	18.635	4.525	91.217	84.320	6.897	92.44%
	60.180	1.664	19.535	4.740	100.127	92.594	7.534	92.48%
384 kHz	9.846	0.298	3.376	0.828	2.929	2.796	0.133	95.45%
	12.636	0.381	4.332	1.063	4.818	4.605	0.213	95.58%
	15.429	0.465	5.294	1.299	7.176	6.878	0.298	95.85%
	17.534	0.529	6.014	1.476	9.267	8.875	0.392	95.77%
	20.328	0.612	6.971	1.711	12.445	11.925	0.520	95.83%
	22.423	0.675	7.690	1.887	15.129	14.507	0.622	95.89%
	25.217	0.758	8.648	2.120	19.117	18.336	0.781	95.92%
	27.311	0.820	9.368	2.296	22.406	21.504	0.902	95.98%
	30.105	0.903	10.327	2.529	27.194	26.112	1.082	96.02%
	32.900	0.986	11.287	2.761	32.446	31.162	1.284	96.04%
	34.995	1.048	12.009	2.935	36.685	35.246	1.439	96.08%
	37.791	1.131	12.971	3.167	42.738	41.079	1.659	96.12%
	39.889	1.193	13.695	3.340	47.576	45.743	1.833	96.15%
	42.678	1.275	14.658	3.571	54.414	52.348	2.066	96.20%
	45.485	1.358	15.626	3.802	61.755	59.413	2.342	96.21%
	47.584	1.419	16.351	3.974	67.526	64.982	2.544	96.23%
	50.381	1.501	17.313	4.205	75.632	72.793	2.839	96.25%
	52.478	1.562	18.038	4.375	81.981	78.916	3.065	96.26%
	55.270	1.644	19.001	4.604	90.853	87.486	3.367	96.29%
	57.380	1.706	19.725	4.777	97.867	94.234	3.633	96.29%
	60.170	1.788	20.692	5.007	107.566	103.611	3.955	96.32%

2.3 P_{OUT}

PVDD-P_{OUT} images are shown in the following figures.

The test conditions for the results in Figure 2-6 and Figure 2-7 include a 1-kHz sine-wave frequency, a 4-Ω resistor, with heat sink, and no airflow.

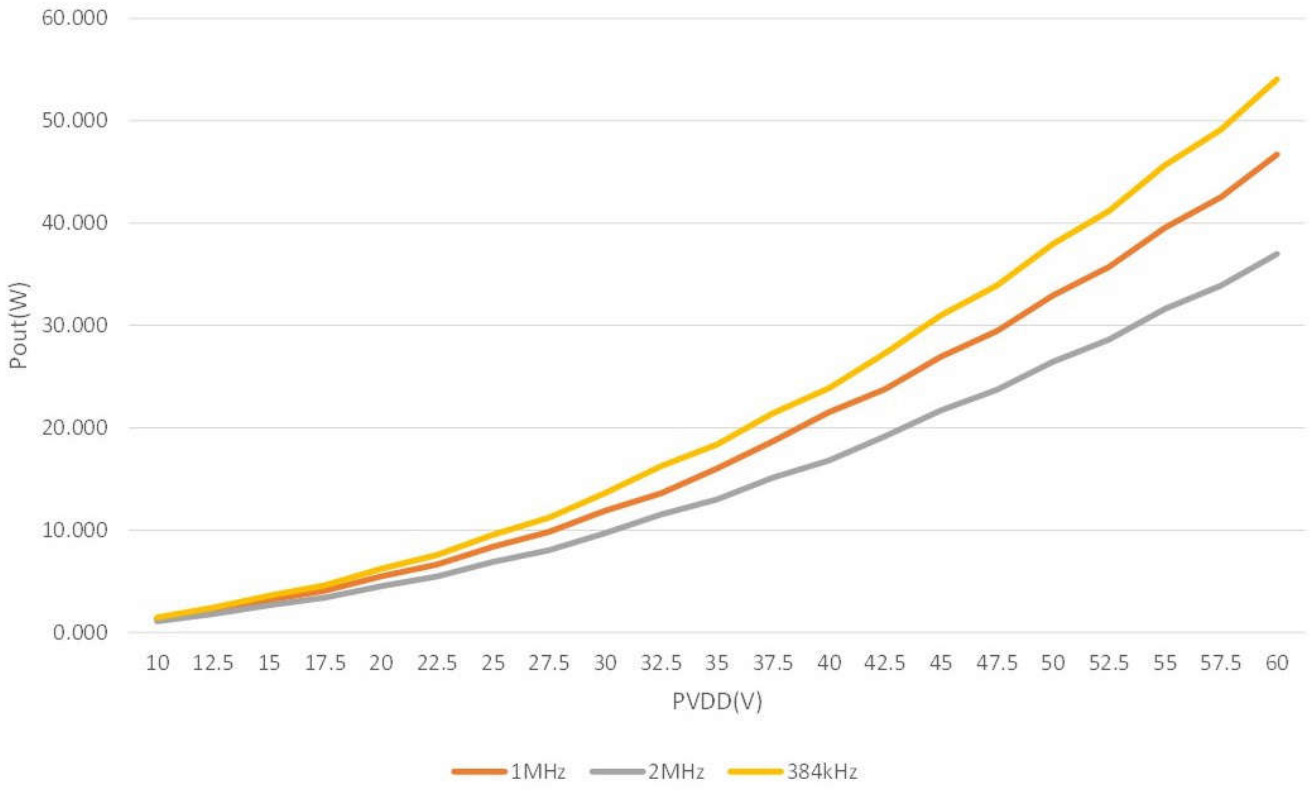


Figure 2-6. P_{OUT} With 0.73 Amplitude Modulation Ratio

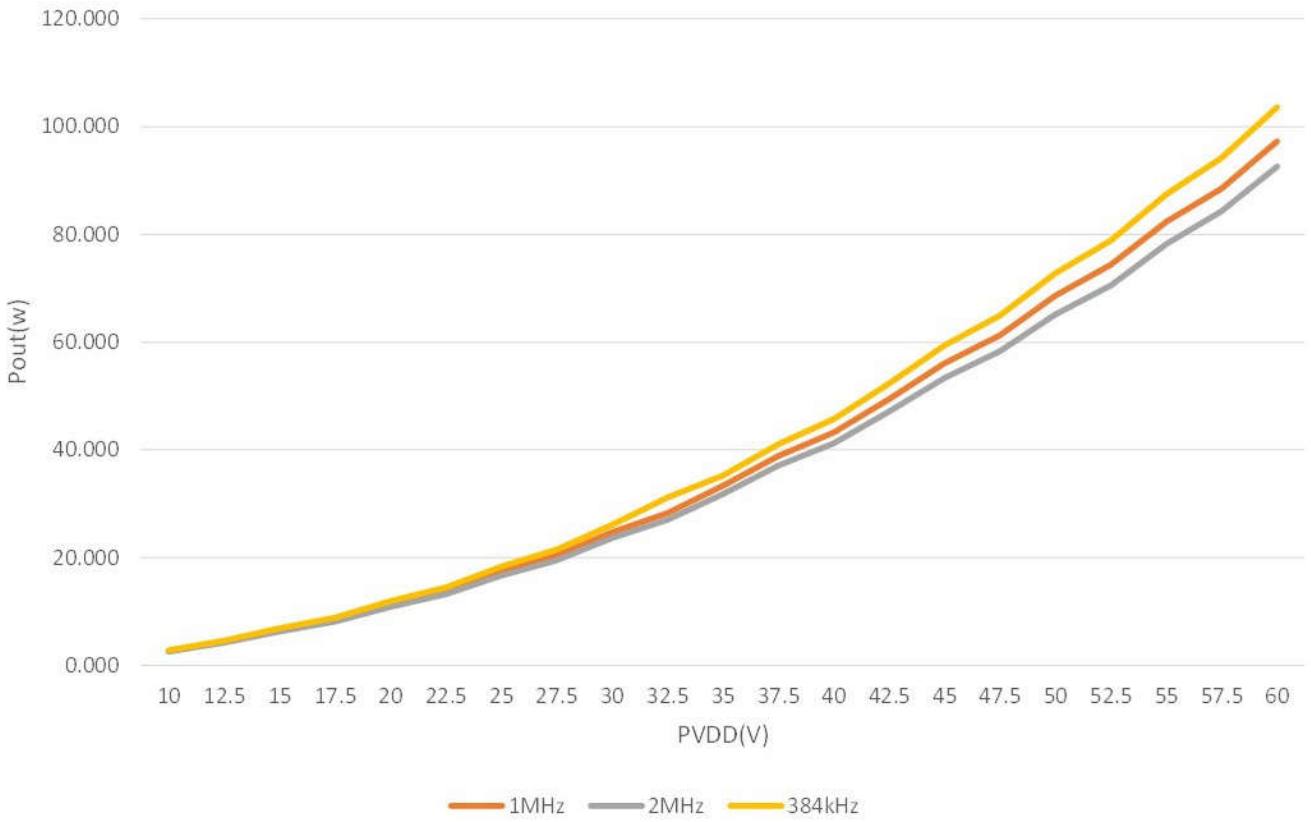


Figure 2-7. P_{OUT} With 1.0 Amplitude Modulation Ratio

2.4 Idle Power Loss

Idle power loss image is shown in the following figure.

The test conditions for the results in Figure 2-8 include a 1-kHz sine-wave frequency, no resistor load, with heat sink, and no airflow.

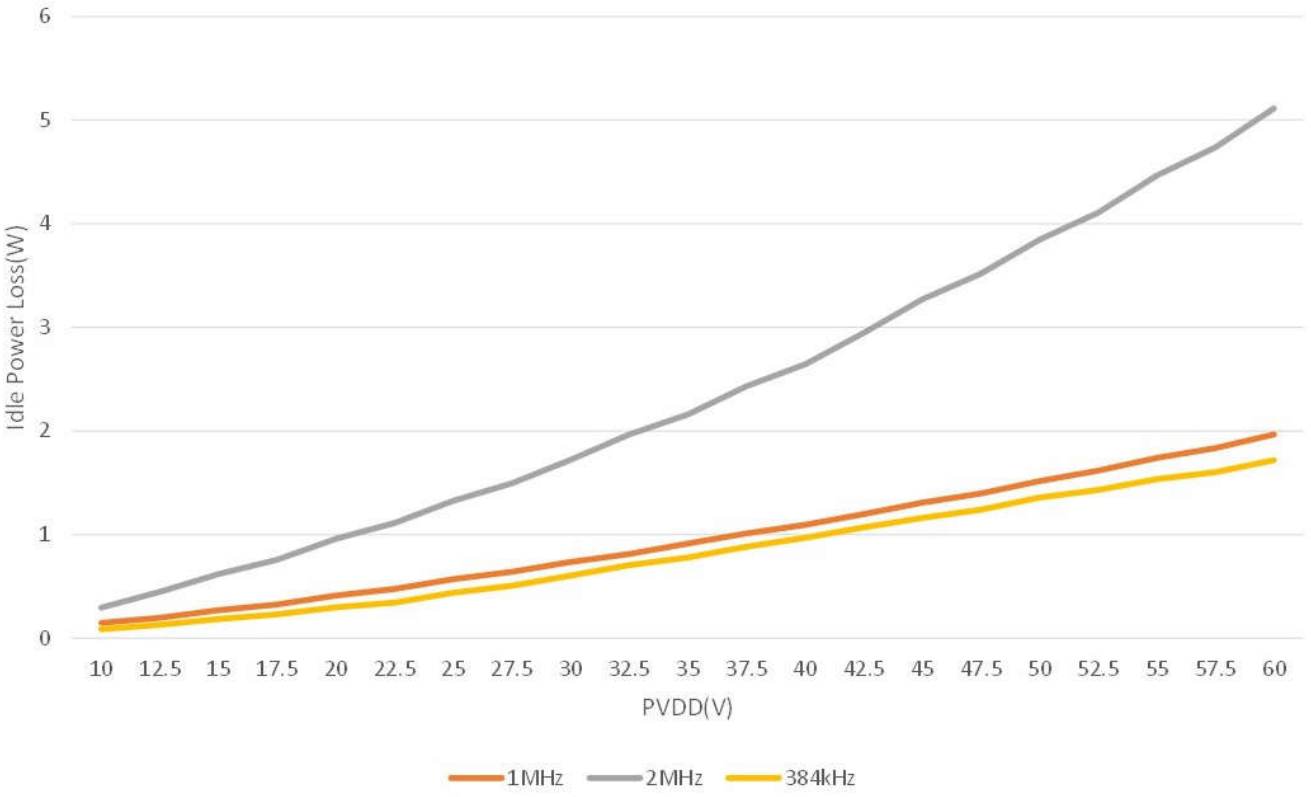


Figure 2-8. Idle Power Loss

2.5 THD

The THD image is shown in the following figure.

The class D power stage is open loop configuration, so the THD data is just for reference. The test conditions for the results in Figure 2-9 include a 1-kHz sine-wave frequency, a 4-Ω resistor with heat sink, and no airflow.

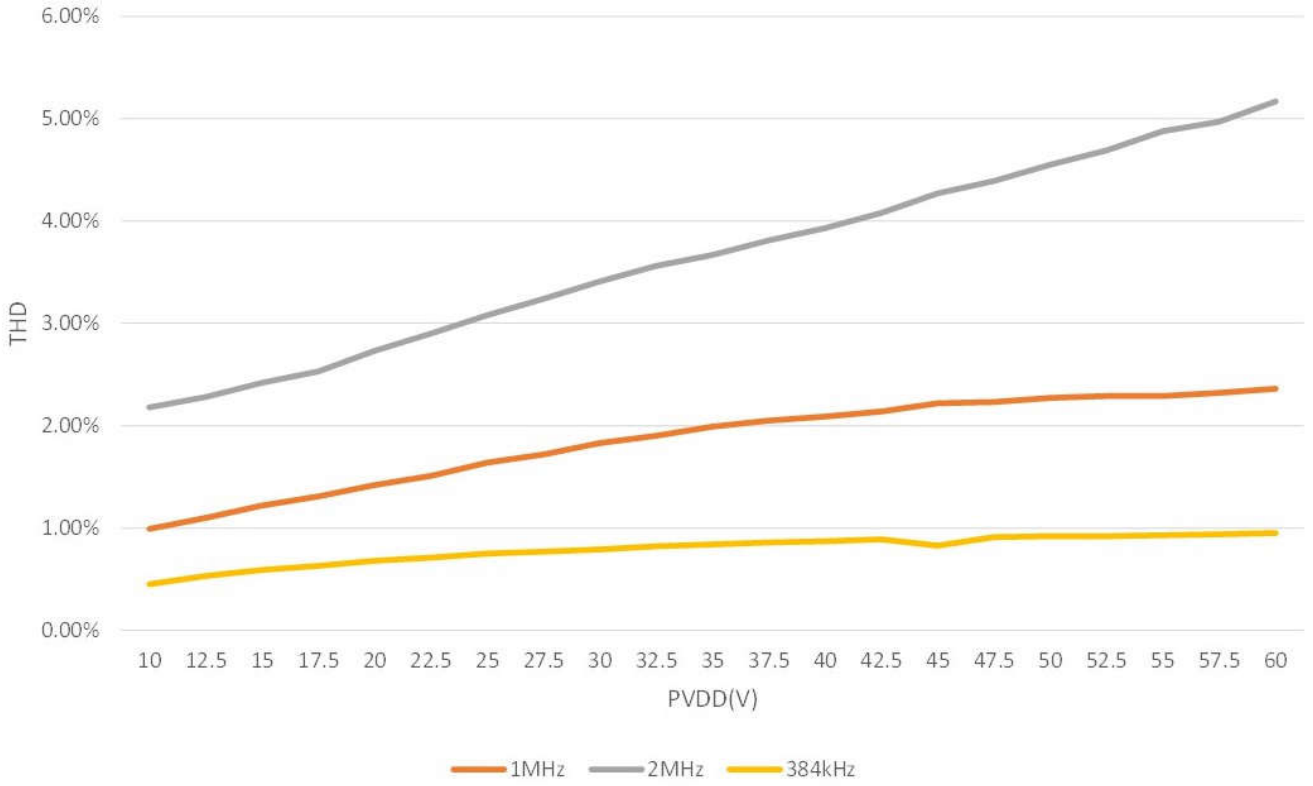


Figure 2-9. THD

2.6 Thermal Images

Thermal images are shown in the following figures.

The test conditions for these images are as follows: 1-MHz switching frequency, 1-kHz sine-wave frequency, 4-Ω resistor, no heat sink, no airflow.

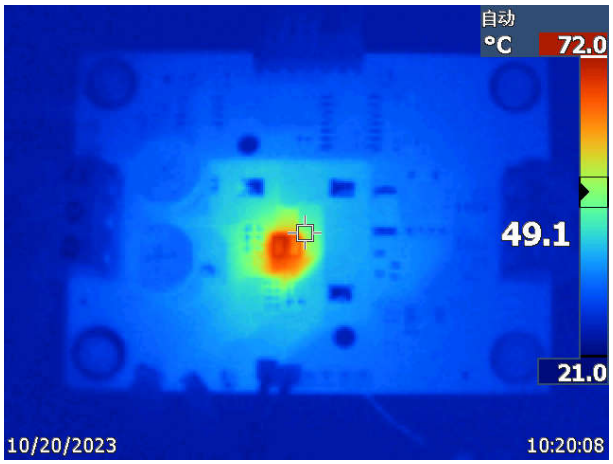


Figure 2-10. Top View Thermal Image at 40-V PVDD

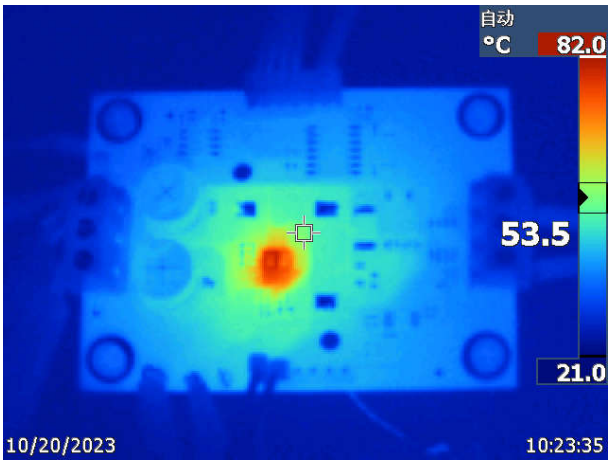


Figure 2-11. Top View Thermal Image at 50-V PVDD

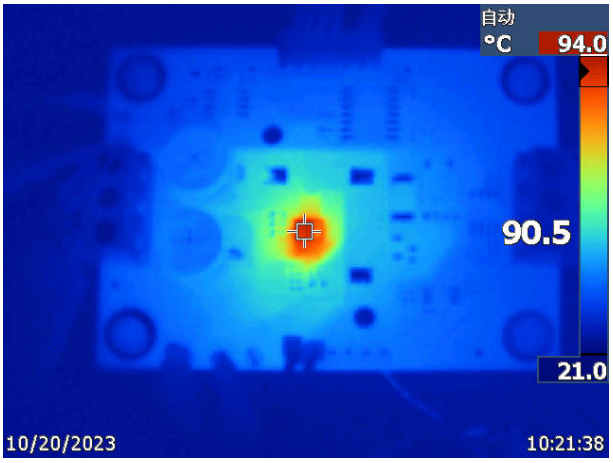


Figure 2-12. Top View Thermal Image at 60-V PVDD

3 Waveforms

Figure 3-1 shows the board schematics.

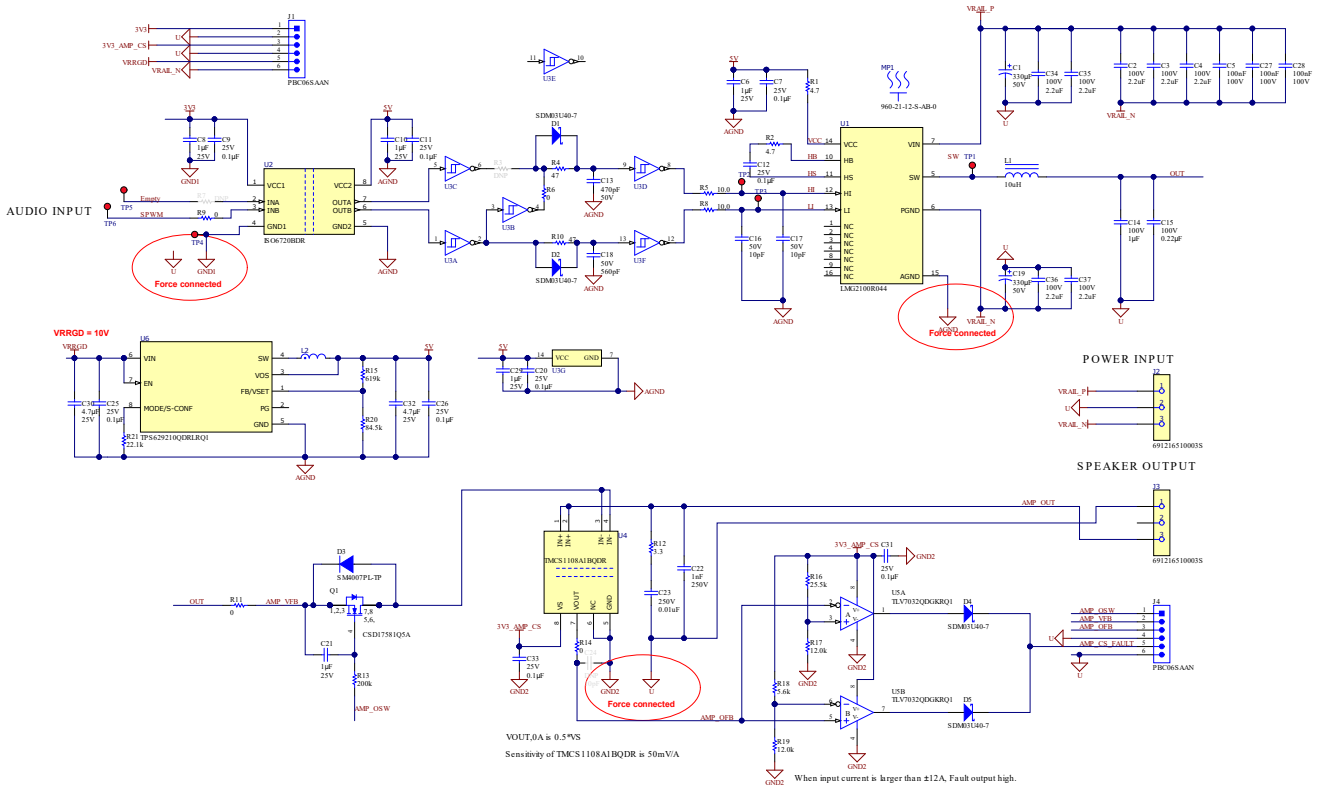


Figure 3-1. Board Schematics

3.1 Switching

Switching behavior at 40-V PVDD is shown in the following figures.

The test conditions for the results shown in Figure 3-2 and Figure 3-3 are 1-MHz switching frequency, 1-kHz sine-wave frequency, 4-Ω resistor, with heat sink, no airflow.

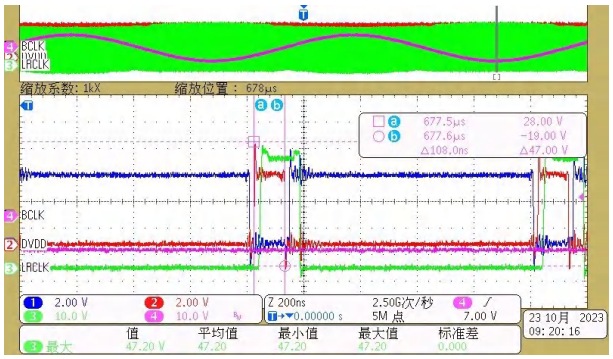


Figure 3-2. Switching Node Voltages of Low-Side GaN(Green) at Bottom of Output Voltage (Pink)

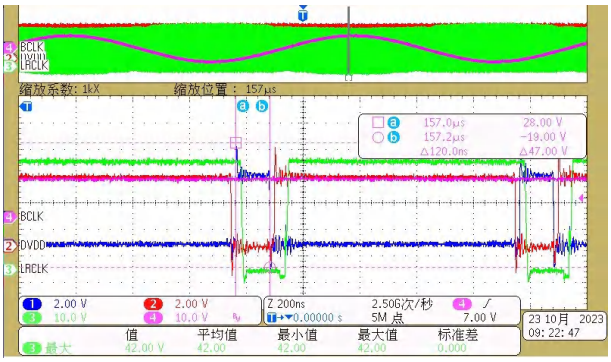


Figure 3-3. Switching Node Voltages of Low-Side GaN(Green) at Top of Output Voltage (Pink)

3.2 Dead Time

Dead time is shown in the following figures.

Dead time can be changed by adjusting the value of C13 and C18. Currently, C13 is 470 pF, C18 is 560 pF, making the dead time around 23 ns.

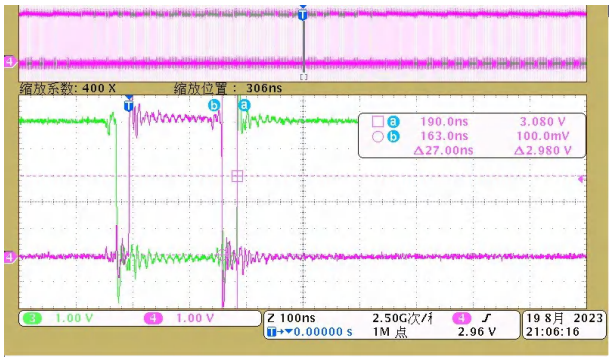


Figure 3-4. Dead Time Between Falling Edge of LI (Pink) and Rising Edge of HI (Green)

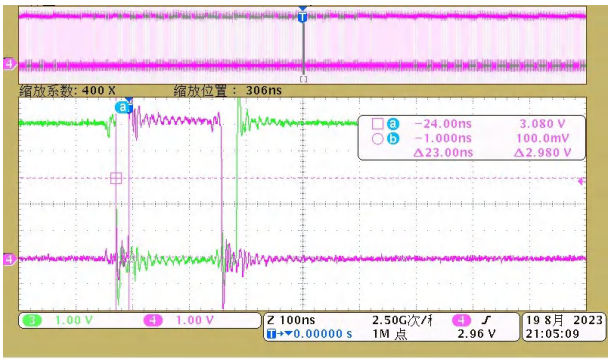


Figure 3-5. Dead Time Between Rising Edge of LI (Pink) and Falling Edge of HI (Green)

3.3 Minimum Pulse on Time of LI

The output voltage waveform at idle load distorts as Figure 3-6 shows when the minimum pulse on time of LI is too small. The limitation for minimum pulse on time is if it is too small, the voltage of the bootstrap capacitor is under UVLO threshold. You can increase the value of C12 to get a smaller minimum on time.

The minimum pulse on time images are shown in the following figures.

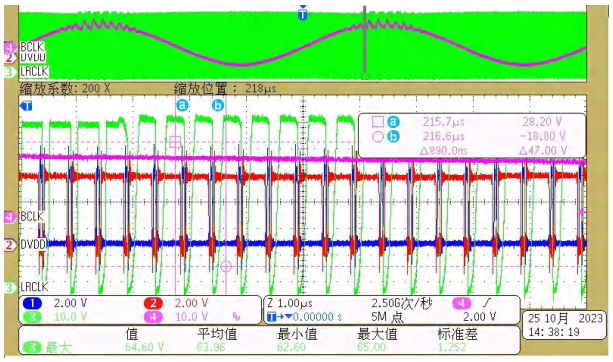


Figure 3-6. Output Voltage (Pink) Oscillate at Idle Load With too Small Pulse on Time of LI (Blue)

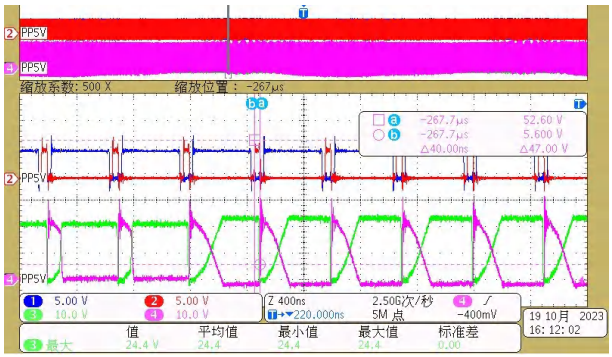


Figure 3-7. Abnormal Vds of High-Side GaN (Pink) and Low-Side GaN (Green) at Idle Load With too Small Pulse on Time of LI (Red)

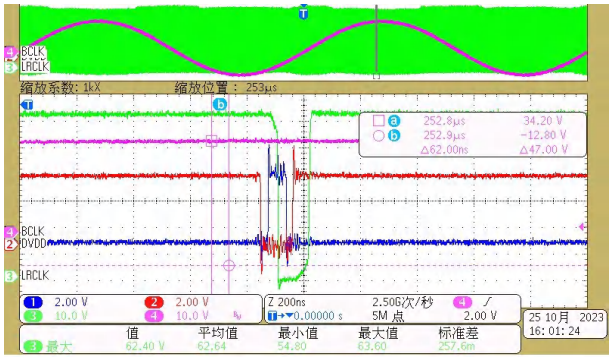


Figure 3-8. Minimum Pulse on Time of LI (Blue) With C12 0.1 µF

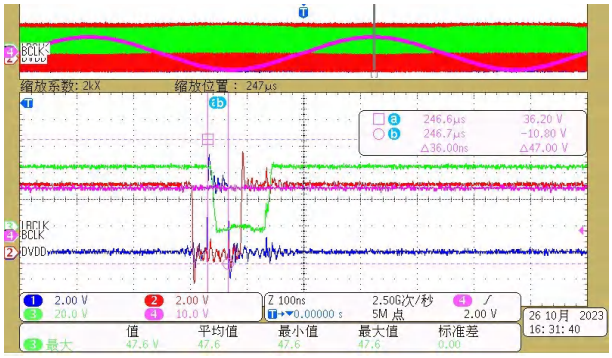


Figure 3-9. Minimum Pulse on Time of LI (Blue) With C12 0.47 µF

3.4 Output Waveform

Output waveform at 60-V PVDD is shown in the following figures.

Test condition: 1-kHz sine-wave frequency, 4-Ω resistor, with heat sink, no airflow.

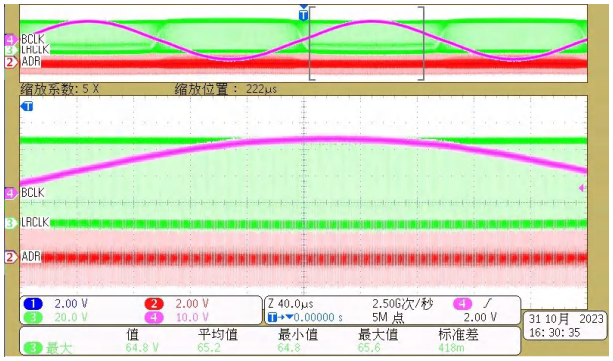


Figure 3-10. Output Waveform (Pink) With 1-MHz Switching Frequency and 0.73 Amplitude Modulation Ratio

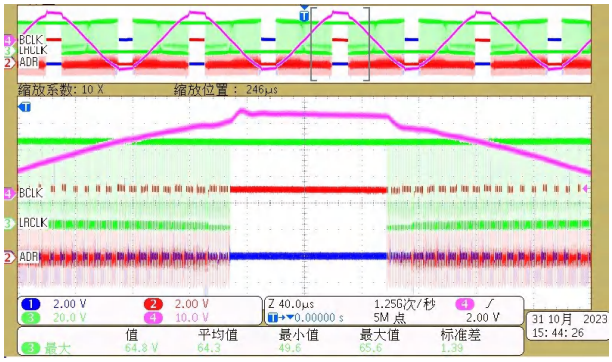


Figure 3-11. Output Waveform (Pink) With 1-MHz Switching Frequency and 1.0 Amplitude Modulation Ratio

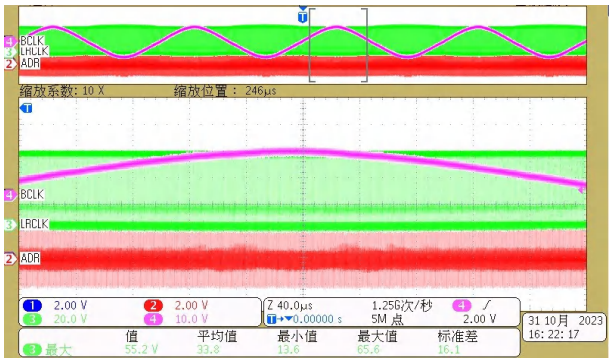


Figure 3-12. Output Waveform (Pink) With 2-MHz Switching Frequency and 0.73 Amplitude Modulation Ratio

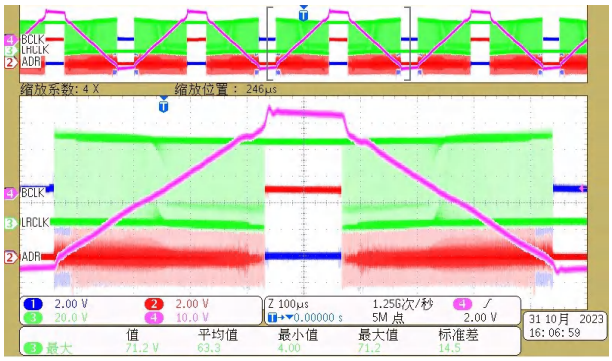


Figure 3-13. Output Waveform (Pink) With 2-MHz Switching Frequency and 1.0 Amplitude Modulation Ratio

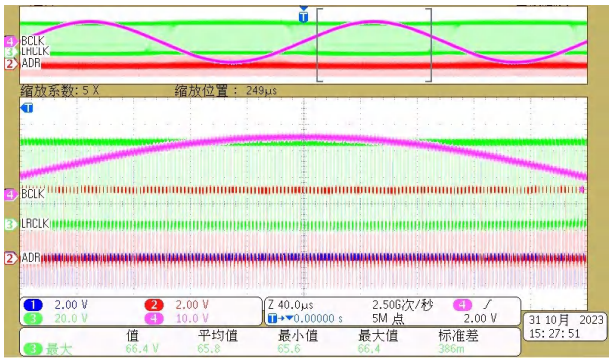


Figure 3-14. Output Waveform (Pink) With 384-kHz Switching Frequency and 0.73 Amplitude Modulation Ratio

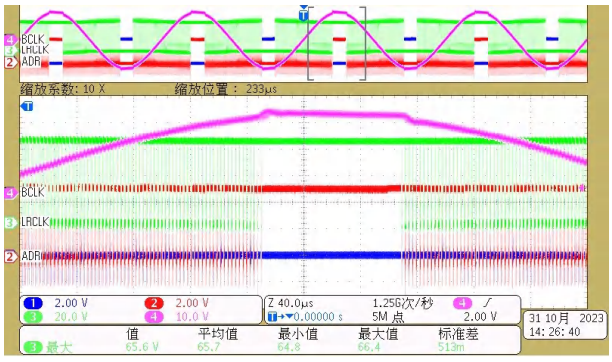


Figure 3-15. Output Waveform (Pink) With 384-kHz Switching Frequency and 1.0 Amplitude Modulation Ratio

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