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Optical Link Tests

Larry D'Addario
California Institute of Technology

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Larry R. D'Addario
California Institute of Technology

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I. INTRODUCTION

This report describes measurements to characterize an RF-over-fiber link using a YiGuDian laser diode (LD, Part Number GLD-PSA2-D3160B-2GR, Serial Number 180516-002) and a YiGuDian photodiode (PD, PN GPD-PSA1-55BR, SN 180511-002). The objective is to characterize the phototonic components alone, without any other circuitry. It complements and extends the results in [1], which were measured on the same units. For RF tests, the laser diode was driven directly from a 50-ohm source, and the photodiode was connected directly to a 50 ohm load. DC bias was supplied through high RF impedances. This means that the source and load were highly mismatched, since the RF impedance of the laser is 4 to 5 ohms and that of the photodiode is many thousands of ohms. However, all measurements were below 100 MHz and connections were via wires no more than 2 cm long.

II. METHODS

The test setup is shown in Figure 1.

The laser diode was on a modified PC board from a DSA110 Front End Box. A short coax cable, about 10 cm long, with an SMA male connector on one end, had the center conductor of its free end soldered to a board trace connected to the laser diode's anode and the outer conductor soldered to board ground. The LD cathode was grounded. Components connecting the laser to other circuitry on the board were removed, and the anode of the photodiode built into the laser package was unsoldered and left open. The receiving photodiode was on a small PCB in an aluminum box; the PCB included only the resistors and capacitors shown in Fig. 1.

A bias tee was used to separate DC and RF connections to the LD. A Keithley 2400 SourceMeter was set to act as a current source for laser bias while measuring the voltage. A second Keithley supply was used to provide 10V bias to the photodiode while measuring its

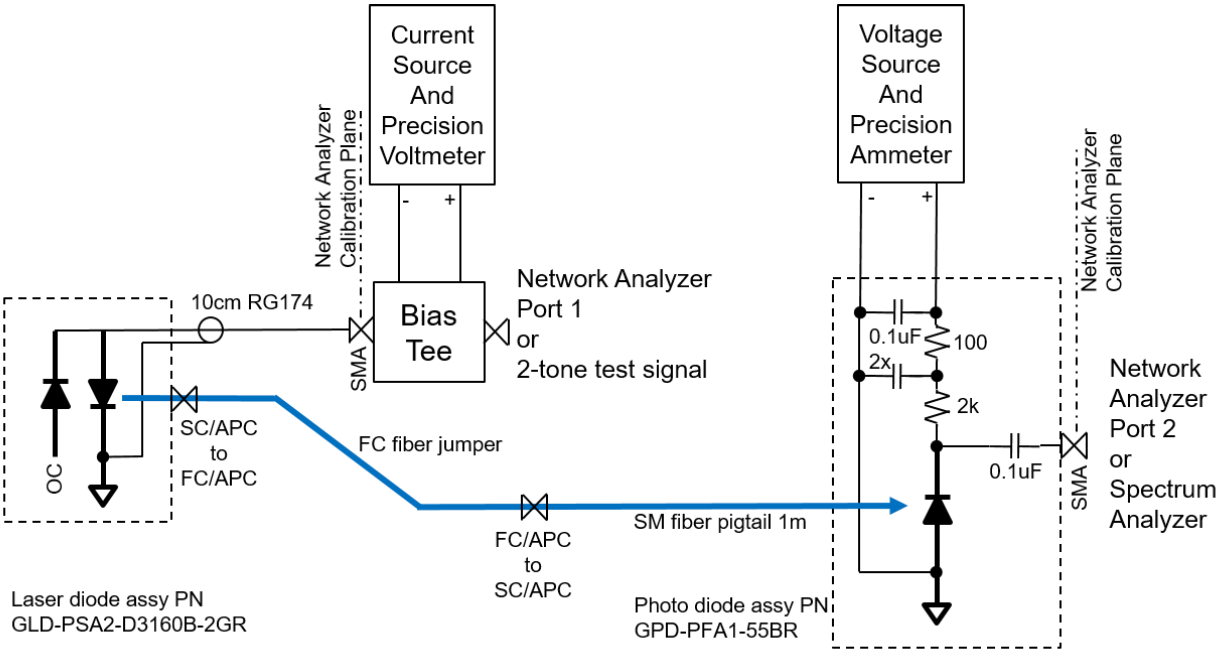


Figure 1. Test setup. The precision sources used for bias are Keithley 2400 SourceMeters. The bias tee is a MiniCircuits ZFBT-4R2GW+.

current.

Measurements were made with laser bias varied from 0 to 25 mA. For DC measurements the RF ports were terminated. Optical power was measured by disconnecting at the FC/SC adapter and connecting the FC jumper to a SainSonic OP600 optical power meter. For impedance and gain measurements, an Agilent 5242A network analyzer was connected as shown in Fig. 1, but Port 1 was calibrated at the laser side of the bias tee. For noise measurements a Siglent SSA3021X spectrum analyzer was connected to the PD and the LD RF port was terminated. For distortion measurements a 2-tone test signal (discussed later) was connected to the LD.

III. MEASUREMENTS

A. DC Characteristics.

The laser current-voltage curve is plotted in Figure 2, along with the differential resistance, $R = dV/dI$. The laser threshold current is about 4.5 mA. Fluctuations in differential resistance between threshold and about 7 mA are believed to be due to insufficient resolution in the voltage measurements and not intrinsic to the laser; the current step was 0.1 mA to 5 mA, then 0.2 mA to 7 mA, then 1 mA. The differential resistance decreases slightly with current, from 4.2 ohms at 6 mA to 4.0 ohms at 20 mA.

Optical power vs. laser current is plotted in Figure 3, along with its derivative. Absolute measurements were made with an optical power meter; separately, the photodiode current was measured. The ratio of these gives a photodiode responsivity of 0.786 A/W; the data sheet give 0.85 A/W minimum, 0.90 A/W typical. The absolute power gives a laser responsivity of 0.14 W/A; the data sheet implies (but does not clearly specify) that this should be 0.20 W/A minimum. Above threshold, the slope dP/dI is very constant. Small fluctuations in slope seen in Fig. 3 are believed to be measurement errors or the effects of fiber movement during the test, rather than intrinsic to the devices.

B. Laser RF impedance and Link Gain.

S parameters were measured with the network analyzer at laser currents of 5, 10, 15, 20, and 25 mA. The analyzer was set for a drive power of –20 dBm; this should produce a swing of ±0.6 mA in laser current. Port 1 was set to add a delay of 333 ps to compensate for the 10 cm of coax between the calibration plane and the laser. The laser impedance varied very little with laser current, except at 5 mA (near threshold); the result for 10 mA is plotted in Figure 4. The real part of the impedance was (5.8Ω, 6.1Ω) at 5 mA and (4.30Ω, 5.0Ω) to (4.19Ω, 5.5Ω) at 10 mA to 25 mA, where the two values are at (20 MHz, 100 MHz).The inductive imaginary part can be removed by setting the analyzer's delay to about 1 ns; the apparent inductance of about 18 nH is too large to be explained by parasitic wires or board traces. There is an apparent resonance that increases the impedance below 17 MHz; this is not understood.

The link gain vs. frequency is plotted in Figure 5 at each laser current. The typical gain of –9.3 dB is about 4.5 dB larger than that calculated from the measured laser impedance, laser responsivity, and photodiode responsivity (see Section IV). The dip in gain below 17 MHz is consistent with the impedance change seen in Fig. 4. The gain increases by 0.1 to 0.3 dB from 20 MHz to 100 MHz; this is not understood. At 100 MHz, gain increases by 0.2 dB as current is increased from 10 mA to 20 mA; this is not consistent with the flatness of responsivity seen in Fig. 3. The gain drops about 2 dB at 5 mA, as expected for operation near threshold. The gain drop at 25 mA, especially at high frequencies, is not understood.

C Distortion.

To measure second- and third-order distortion, a two-tone test signal was created using the setup in Figure 6. The tones were at f_1 = 19.0 and f_2 = 20.0 MHz, resulting in distortion products at 18, 21, and 39 MHz, none of which is a harmonic of the input tones, as well as at other frequencies. Results are therefore immune to harmonics in the signal sources, but the setup includes a 21.7 MHz low-pass filter to ensure that the test signal harmonic content is very low. With a 10 dB attenuator just before the bias tee, the tone levels at the bias tee output were -22.3 and -22.1 dBm. Spectra at the photodiode are plotted in Figure 7.

The spectrum analyzer was set to resolution bandwidth 10 kHz, input attenuation 0 dB, and preamp off. The frequency span (30 MHz) was chosen so that all frequencies of interest fall in the center of resolution bins. The spectra were recorded to files for numerical analysis, giving the results in Tables 1 and 2. Measurements were also made with a 6 dB pad before the bias tee, so that the test tone levels were about 4 dB higher. In Table 2, the 2nd-order intercept IP2 and 3rd-order intercept IP3 are calculated from the data in Table 1. IP2 is calculated in three ways, using the 2nd harmonics of f_1 and f_2 as well as $f_1 + f_2$. IP3 is calculated in two ways. The results mostly agree within ~1 dB.

For small signals, a 4 dB increase in input power should cause the 2nd-order products to increase by 8 dB and the 3rd-order products to increase by 12 dB. The increases were mostly about 9 dB and 11 dB, respectively, suggesting that higher-order products may be significant at the higher signal level.

Table 1: Two-tone tests

	I_LD	*power (dBm) at frequency (MHz)*						
	mA	18	19	20	21	38	39	40
10dB pad	10	-87.24	-32.23	-32.16	-87.47	-96.40	-89.91	-94.76
	15	-87.17	-32.23	-32.16	-87.79	-98.38	-92.39	-96.69
	20	-87.21	-32.21	-32.14	-87.68	-101.34	-98.58	-102.11
	25	-84.75	-32.35	-32.29	-84.58	-74.70	-68.01	-73.72
6dB pad	10	-76.48	-28.48	-28.37	-76.32	-85.24	-80.76	-84.39
	15	-76.39	-28.47	-28.35	-76.57	-89.34	-83.02	-88.46
	20	-76.42	-28.48	-28.36	-76.62	-97.63	-92.52	-96.70
	25	-76.44	-28.56	-28.45	-76.70	-67.06	-60.43	-65.98

Table 2: Calculated 2nd and 3rd Order Intercepts

	I_LD	*IP2, dBm*			*IP3, dBm*	
	mA	f1	f2	f1+f2	2f2-f1	2f1-f2
10dB pad	10	31.94	30.44	31.45	-4.72	-4.61
	15	33.93	32.36	33.93	-4.76	-4.45
	20	36.91	37.82	40.15	-4.71	-4.48
	25	10.01	9.14	9.31	-6.15	-6.23
6dB pad	10	28.27	27.65	29.80	-4.48	-4.56
	15	32.40	31.75	32.08	-4.51	-4.42
	20	40.67	39.97	41.56	-4.51	-4.41
	25	9.95	9.08	9.31	-4.62	-4.49

Distortion products were about the same for laser currents of 10, 15, and 20 mA, but at 25 mA 2nd order products were 25 to 30 dB worse and 3rd order products were 2.5 to 3 dB worse. This is consistent with the drop in gain at 25 mA (Fig 4). We see no evidence of this in the DC characteristics (Figs. 1 and 2), but the DC measurements were not carried to high enough currents.

D. Link Noise.

With the LD RF port terminated and the spectrum analyzer connected directly to the PD (no external preamplifier), the noise was measured with settings resolution bandwidth 1 MHz, attenuation 0 dB, internal preamp on; and at laser currents of 5, 10, 15, 20, and 25 mA. Results are summarized in Table 3 and a typical spectrum is shown in Figure 7.

Table 3: Link Noise Measurements

	I_{PD}	10 MHz		20 MHz		50 MHz		100 MHz		T_{shot}	T_{RIN}(-161.7)	$T_{shot}+T_{RIN}$
	mA	dBm/Hz	K	dBm/Hz	K	dBm/Hz	K	dBm/Hz	K	K	K	K
SA term.		-164.52	2558	-164.77	2415	-164.55	2540	-164.56	2535			
$I_L = 0$	0.0000	***-164.51***	***2564***	***-164.49***	***2576***	***-165.09***	***2243***	***-164.56***	***2535***	0	0	0
I_L = 5 mA	0.1508	-159.66	5269	-160.56	3791	-159.42	6034	-159.58	5444	175	6	181
I_L = 10 mA	1.1300	-161.72	2310	-162.34	1650	-162.11	2212	-161.20	2960	1311	313	1624
I_L = 15 mA	2.1281	-160.72	3572	-161.43	2635	-161.04	3457	-160.70	3630	2470	1109	3578
I_L = 20 mA	3.1152	-159.83	4968	-160.64	3675	-160.09	4851	-160.17	4430	3615	2376	5991
I_L = 25 mA	4.0960	-159.23	6084	-160.45	3954	-160.82	3753	-161.91	2131	4753	4108	8861

In Table 3, the measurements in dBm/Hz are those read from the spectrum analyzer. Those at laser current $I_L = 0$ are considered to represent the analyzer noise; for those at $I_L > 0$, the analyzer noise is subtracted from the results in K to give the noise of the link alone. The last three columns of the table are calculated from the photodiode current I_{PD} as

$$T_{shot} = 2\, e\, I_{PD}\, R_0 / k$$

$$T_{RIN} = R_0\, I_{PD}^{\,2}\, N / k$$

where e is the charge of an electron, R_0 = 50 ohms is the load resistance due to the spectrum analyzer, N is the relative intensity noise (RIN) of the laser, and k is Boltzman's constant. The shot noise result T_{shot} should be very reliable. T_{RIN} is calculated for $N = -161.7$ dB to fit the measured noise at I_L = 15 mA. This is not a good fit at other currents because N typically decreases with laser current. This indicates that the laser noise is very low; we see mostly shot noise for $I_L \geq 15$ mA.

IV. DISCUSSION

The real part of the RF impedance of the laser agrees very well with its differential DC resistance, about 4.2 ohms at 20 MHz vs. 4.0 ohms at DC. It appears to increase with frequency, but only to 5.0-5.5 ohms at 100 MHz; this could be the effect of parasitic reactances. At all frequencies below 100 MHz, the impedance is low enough that driving with a 50 ohm source is a good approximation to driving with a current source.

At laser current of 25 mA, we see increased distortion (Table 2) and decreased high-frequency gain (Figure 5). These are unexpected and do not seem to be consistent with the DC measurements.

The measured link gain is larger than what is predicted from the DC measurements by a simple theory. We measure $G = |S_{21}|^2$, which is the ratio of the power delivered to a 50 ohm load to the power available from a 50 ohm source. Neglecting all reactances, this should be

$$G = [2\,\alpha\,\beta\,G_{opt}\,R_0\,/(R_0 + R_L)]^2$$

where α is the laser responsivity (dP/dI_{LD}), β is the photodiode responsivity (dI_{PD}/dP), G_{opt} is the optical power gain (loss in fiber), R_0 = 50 ohms is the source and load resistance, and R_L is the laser's RF resistance. Using the measured values of α = 0.14 W/A, β = 0.786 A/W, R_L = 4 ohms and assuming G_{opt} = 1.0 (0.0 dB) gives G = –13.8 dB. We measure –9.3 to –9.1 dB. It is hard to explain this discrepancy of 4.5 to 4.7 dB. Correction for anything that might have been neglected in the theory (reactances, fiber loss) would make the calculated gain lower, not higher. Our measurements of LD and PD responsiviities for these units (delivered in May 2018) are below the specifications on their data sheets; if the responsivities had the minimum values of the data sheets (α > 0.2 W/A, β > 0.9 A/W) the calculated gain would have been G > –9.5 dB.

V. ADDITIONAL WORK NEEDED

The indications of unexpected distortion at laser currents above 20 mA seen in these tests should be further investigated. For applications requiring high dynamic range, it may be desirable to operate these lasers at high current.

The results reported here are for a single laser and photodiode, but many devices of the same types have been purchased for DSA110 and more are intended to be purchased for LWA352. It is important to test at least a few more to check reproducibility. In particular, the responsivities of both the laser and photodiode tested here are below the minima given on the data sheets and below those given in factory test data on newer units.

REFERENCE

[1] S. Weinreb, "Tests of Laser Link Noise and Harmonics in the 10 to 100 MHz Range." LWA-OVRO internal report, 2019 Nov 23.

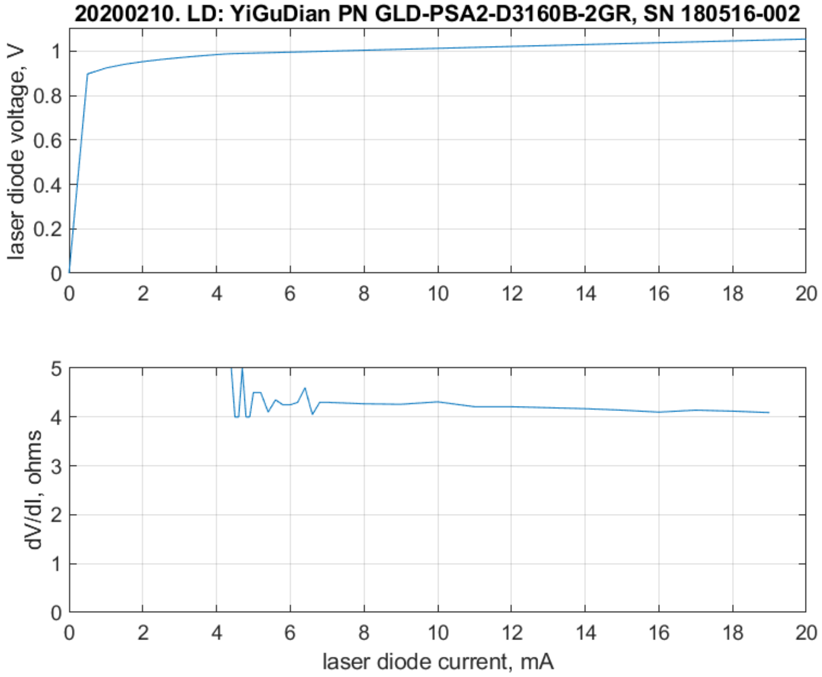


Figure 2. *Top:* Laser voltage-vs.-current measurement. *Bottom:* Calculated differential resistance, *dV/dI*. .

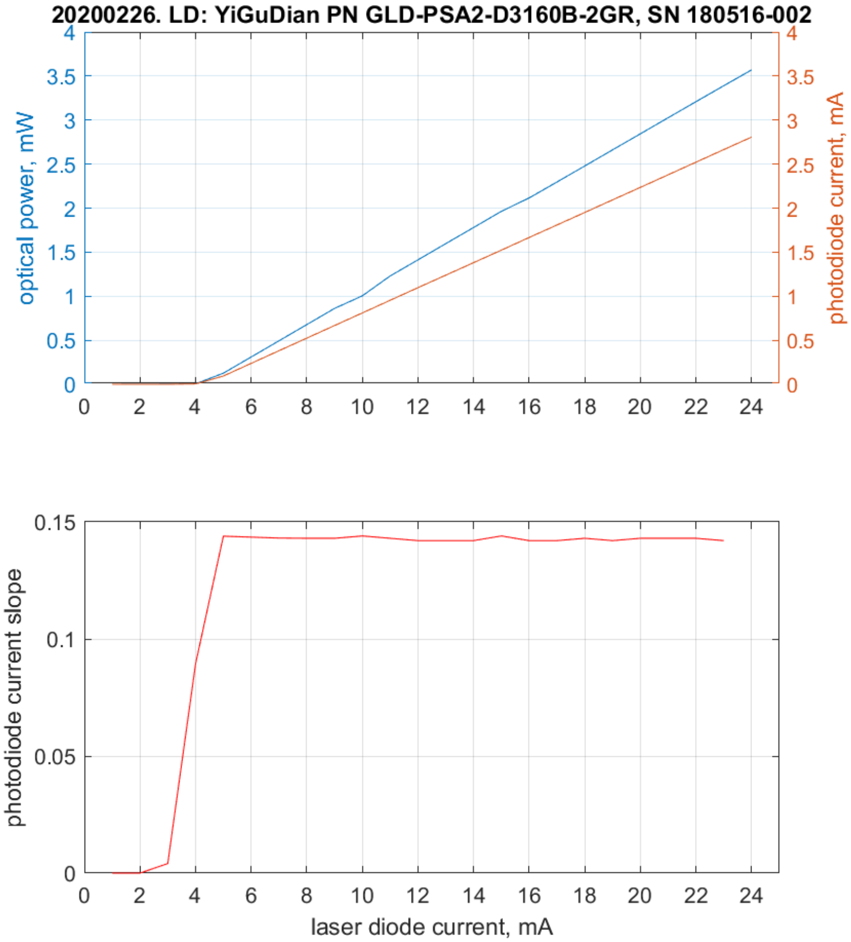


Figure 3. *Top:* Optical power vs. laser current (blue) and photodiode current vs laser current (red). *Bottom:* *Bottom:* Calculated slope, dI_{PD}/dI_{LD}. .

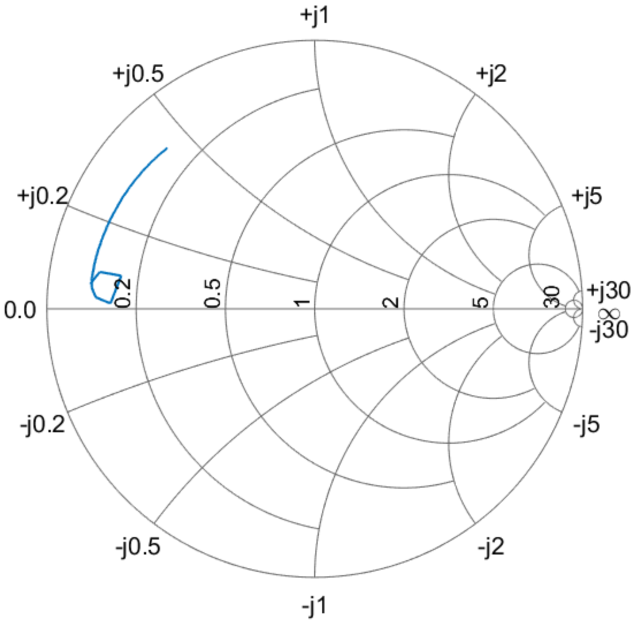


Figure 4. Network analyzer measurement of laser reflection coefficient (S11) relative to 50 ohms. This measurement was made at 10 mA laser current, but there was little change with current. A delay of 333 ps was applied to the measurements. See Fig. 1.

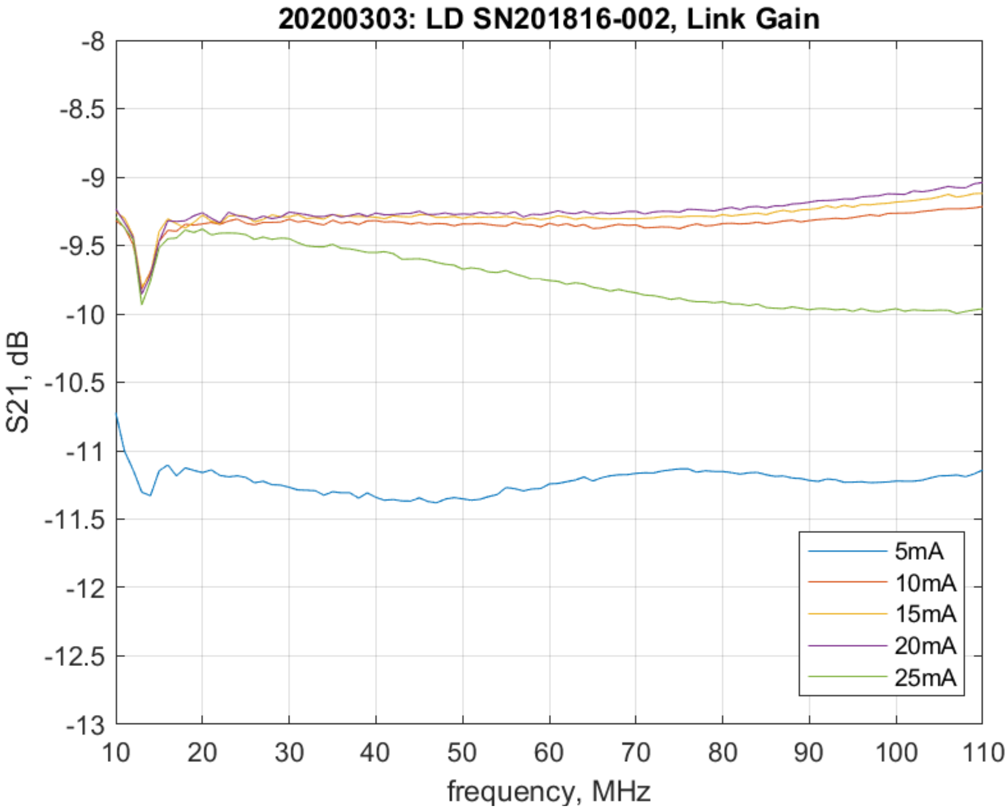


Figure 5. Network analyzer measurement of link gain (|S21|) at several laser currents. The reduced gain at 5 mA (near threshold) is expected, but the drop in high-frequency gain at 25 mA is not. The network analyzer signal level was set to –20 dBm, which should produce a current swing of ±0.6 mA from the bias point.

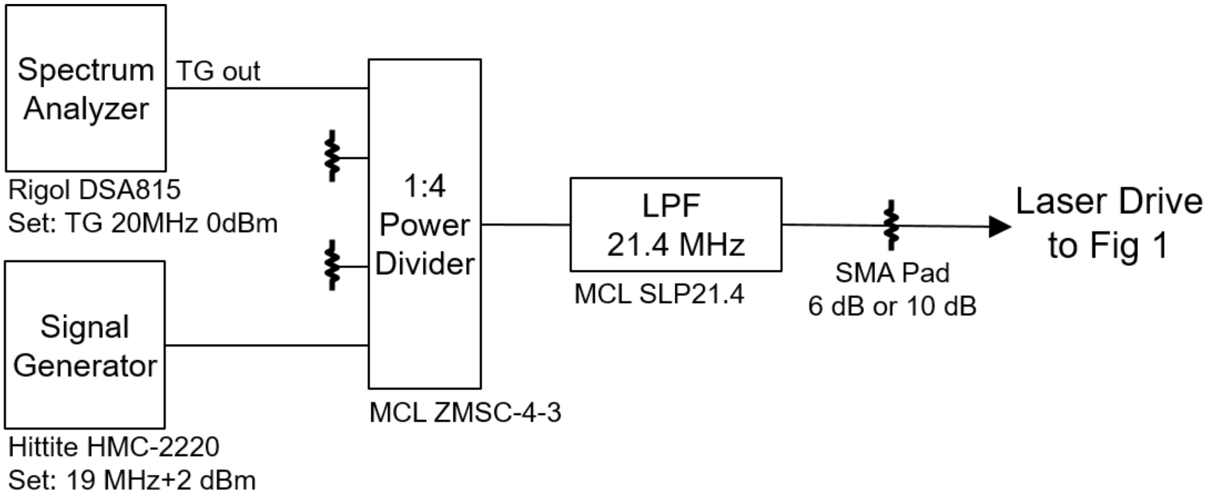
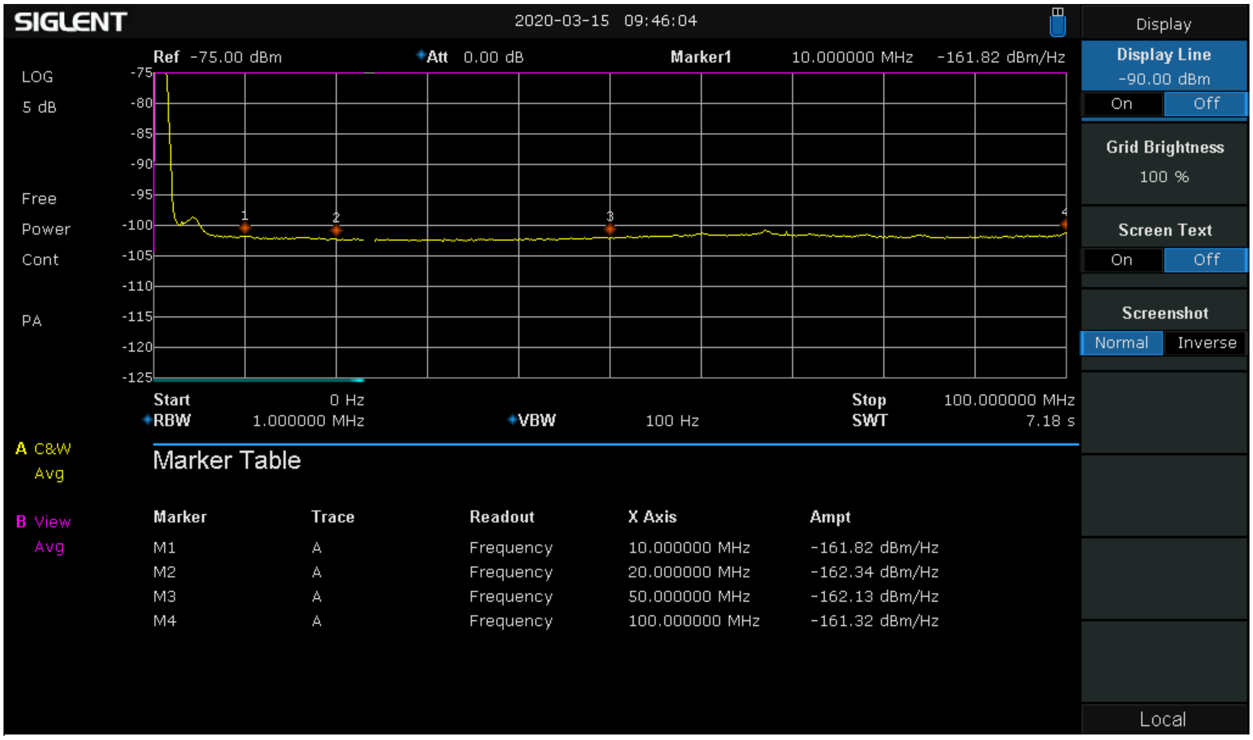


Figure 6. Setup for generating the two-tone signal for the distortion measurements. With the 10 dB pad installed, the sources were set so that each tone delivered –22.2 dBm into 50 ohms at the laser drive point (after the bias tee in Fig. 1).



Ref -75.00 dBm
Att 0.00 dB
Marker1 10.000000 MHz -161.82 dBm/Hz
Start 0 Hz
RBW 1.000000 MHz
VBW 100 Hz
Stop 100.000000 MHz
SWT 7.18 s

Marker Table

Marker	Trace	Readout	X Axis	Ampt
M1	A	Frequency	10.000000 MHz	-161.82 dBm/Hz
M2	A	Frequency	20.000000 MHz	-162.34 dBm/Hz
M3	A	Frequency	50.000000 MHz	-162.13 dBm/Hz
M4	A	Frequency	100.000000 MHz	-161.32 dBm/Hz

Figure 7. Noise spectrum at photodiode with 50 ohm termination at laser. This measurement was taken at 10 mA laser current. The noise floor (laser off) was –164.5 to –165.1 dBm/Hz. See Table 3 for additional results.