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Power Stability and Beam Quality of the LIGO 126 MOPA Lightwave Lasers

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Introduction

A number of measurements have been done with the aim to characterize the laser 126MOPA, designed and developed under contract with LIGO by Lightwave Electronics Inc.

In particular, the beam quality and the power stability has been tested, because they seems to be the "weak points" for almost the 5 lasers already delivered.

1 Long and Short Term Laser Power Fluctuations

The relative power fluctuation specified for the free running 126MOPA laser, are the following:

$$\frac{\Delta P}{\langle P \rangle} < 1\% \text{ peak-to-peak}, \qquad (\text{ over 24 hours}), \tag{1}$$

$$\frac{\Delta P}{\langle P \rangle} < 3\% \text{ peak-to-peak}, \qquad (\text{over 500 hours}). \tag{2}$$

The following section, reports the results obtained on the 3 lasers, monitoring the output power of the Power Amplifier and the Master Oscillator.

To measure the output powers it has been used the calorimeter gentec PS330WB350 for the high power output and the photo-detector located inside the 126MOPA, for the master oscillator output power (amplified using the Stanford Research SR 560) The data acquisition has been done using the ADC card National Instruments AT-MIO-16XE-10 , and the LabView interface.

1.1 126MOPA#103 Power Fluctuations

The test on the 126MOPA#103 has been conducted after a maintenance done to restore the output power level and the beam mode quality. During this operation, it has been decided to increase the laser diode current of 1A to reach the needed output of about 11.2 W. Moreover, one of the folding mirror inside the power amplifier has been found completely free and it has been re-glued .

The result of the power fluctuation test for the 126MOPA#103 reported in figure 1, shows a degradation on the output power not correlated to the NPRO output power (the NPRO power goes up) and a relative fluctuation of 8 %. After 3 days since the end of the test the power has decreased down to 9.4 W.

This behavior has suggested the possibility of a degradation on the performances of the pumping laser diodes of the power amplifier. In fact when the laser has been sent back to the Lightwave, three of the eight laser diodes of the power amplifier, have been replaced.

A possible hypothesis to explain the degradation of the laser diodes efficiency, could be the temperature, too high inside the power amplifier head.

A coarse monitoring of the external temperature of the amplifier head has been done during the tests on the other lasers.

The fact of one of the folding mirror of the power amplifier has been re-glued, could be a symptom of problem of thermo-mechanical stability of the power amplifier, that can explain a non constant performance on the power output, often experienced, when the lasers have been turned on, after a long shut-off period. For example, an hysteresis on the yaw of the glued mirrors, during subsequent warm-up of the laser, can partially modify the correct alignment of the power amplifier head.

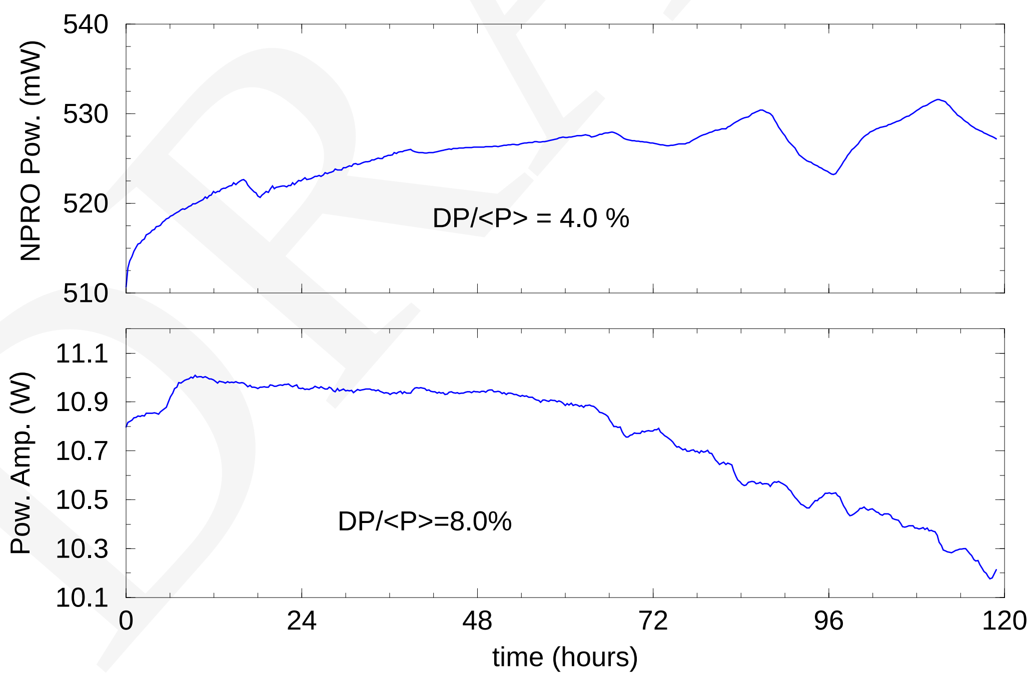


Figure 1: Output Power versus time of the power amplifier and the NPRO of the 126MOPA#103. The power decay of the power amplifier is due to the rapid efficiency degradation of some of the pumping laser diodes.

1.2 126MOPA#104 Power Fluctuations

The output power of the 126MOPA#104 laser turned on for the first time, several months ago in Caltech, was about 11.2 W, after a warm-up of about 2 days.

The results of the test done several months later, shows an average power of 10.6W, a trade off of 5% as reported in figure 2.

The power fluctuations are 8% (considering also a 2 days of warm-up) .

Analyzing the figure 2, a 24 hour periodicity can be seen specially in the power amplifier output signal, for the presence of a sequence of almost equal-spaced bumps.

After 10 days since the end of the test, the power amplifier output has decreased down to 9.4 W. The total roll off from the beginning is then of about 17%.

It has to be pointed out, that the laser has suffered many intervention on the alignment, to try to bring the power up to the required level.

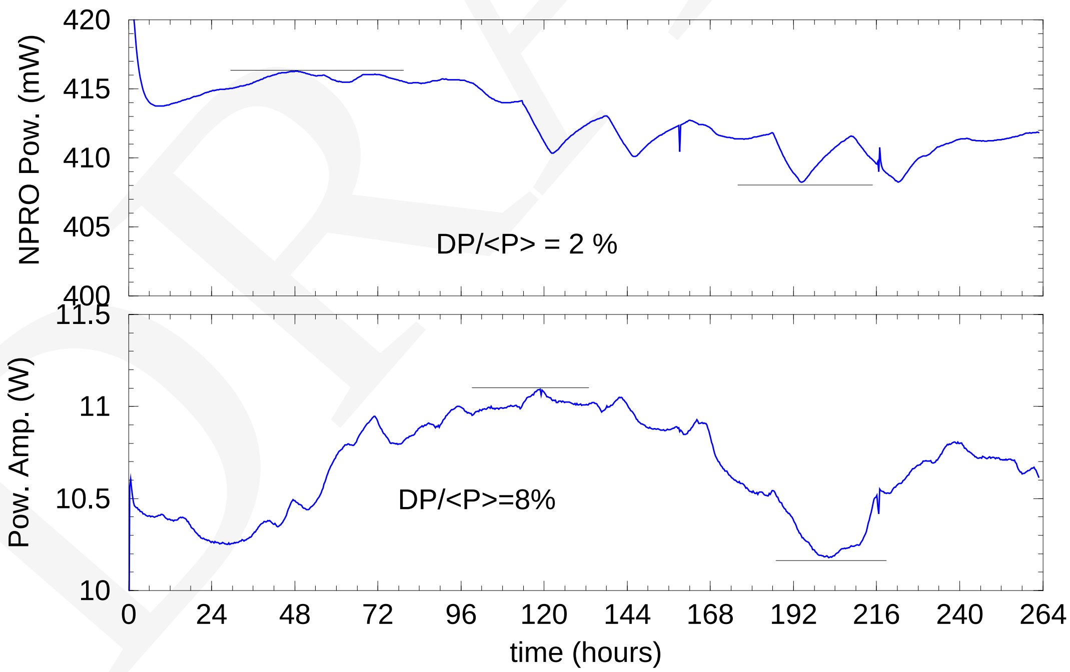


Figure 2: Output Power versus time of the power amplifier and the NPRO of the 126MOPA#104. After 10 days since the end of the test, the power amplifier output has decreased down to 9.4 W.

1.3 126MOPA#107 Power Fluctuations

The test performed on the 126MOPA#107, has given the best results with an average power of 10.3 W and a power fluctuation of 0.5% during a period of 7 days and considering a warm-up of about 24 hours.

A contemporary monitoring, for a shorter period , of the output power using the calorimeter has been done for the photodetector calibration (1 day).

Figure 3 shows the power amplifier output and the NPRO output both monitored using the internal photodetector inside the laser.

In this case the power fluctuations of the power amplifier can be explained by those ones of the master oscillator (both has the same order of magnitude).

Although it easy to notice a strong correlation between the NPRO power output and the power amplifier output, for the first 18 hours in the figure 3, for the subsequent days is not so evident. No real correlation analysis has been done for those signals.

The peak on the power amplifier signal in figure 3, is not easy to explain with the available data. Anyway, a naive attempt can be done, if we suppose that the NPRO is mode hopping or simply, is changing the frequency. This effect could produce an involuntary better tuning of the wavelength light impinging into the power amplifier, which increases suddenly the laser diode pumping efficiency and generates the peak.

During a second running period of 8 days, when the laser has been turned on to conduct other tests, a decreasing power trend has been observed, from a maximum of 9.4 W to a minimum of 9.2 W output power.

Considering these values, obtained without a continuous monitoring, the relative power fluctuation are about 2 %.

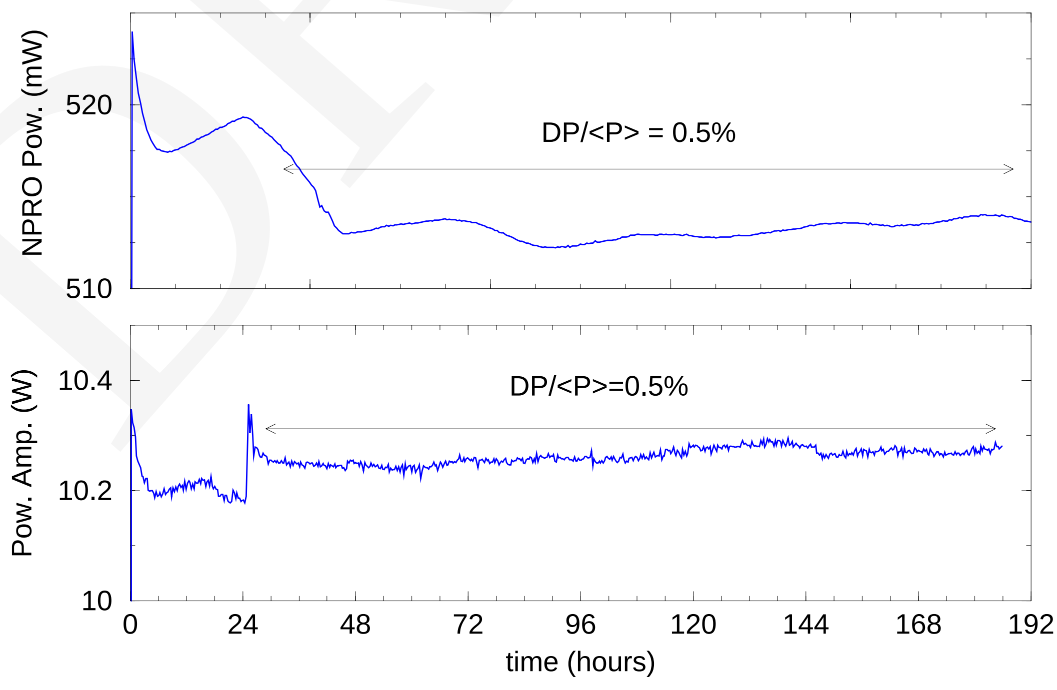


Figure 3: Output Power versus time of the power amplifier and the NPRO of the 126MOPA#107.

1.4 Resume

In the first following table are resumed the relative power fluctuation measured for the 3 laser, tested for long term periods. The last column contains the last value of the laser power output available, without any intervention on the alignment and on the laser diodes current level.

Laser	$\langle P \rangle$	$\frac{\Delta P}{\langle P \rangle}$	Long period	Initial	Current
	(long period)	(long period)		Power	Power
s/n	(W)	(%)	(days)	(W)	(w)
103	~ 10.6	8.0	5	N.A.	9.9 (12/18/98)
104	10.6	8.0	11	11.2	9.4 (01/21/99)
107	10.3	0.5	7	10.3	9.3 (03/15/99)

The second table contains the homologue data for the respective non-planar-ring-lasers used to drive the power amplifiers.

NPRO	$\langle P \rangle$	$\frac{\Delta P}{\langle P \rangle}$	Long period
Laser	(long period)	(long period)	
s/n	(mW)	(%)	(days)
103	~ 525	4.0	5
104	413	8.0	11
107	514	0.5	7

Considering the continuous monitoring and the power measurements conducted during different running periods, the 3 lasers show relative power fluctuations greater than needed.

A possible reason of these fluctuation could be an inadequate temperature stabilization of the power amplifier head. A large difference from the chiller temperature and the cover of the power amplifier (about $10°C$ for the 126MOPA#104) can explain a low sensitivity on the temperature fluctuation on the laser diodes (the probe is probably too far from the laser diodes junctions or/and it is not sitting onto the structure which hold the diodes).

Another source of instability, could be the use of one probe for all the laser diodes. Obviously, in this configuration the sensor is unable to track the temperature each diode or to sample the average of the 8 diodes but it measures essentially, the temperature of the closest one[1].

Moreover a negative trend of the output power not explainable by the behavior of the master oscillators lasers, has been clearly noticed for the all the laser tested in Caltech.

2 126MOPA s/n 103R Beam Profile

This measurements has been done after the substitution done by Lightwave, of 3 pumping laser diodes of the power amplifier head (the R letter after the number 103 stands for "rebuilt"). The total running time at the end of all the measurements was $\sim$ 3600 hours. The temperature of the chiller was 27.5°C, the total laser diodes current 22.60 A and the output power of about (11.3 ± 0.1) W.

2.1 M^2 Measurements

Measurement of the M^2 parameter has been done using the PHOTON Beam Scan and a dedicated software PBAS-Windows v.3.5d. The typical time needed to perform each measurements, was about 40 minutes.

The measures has been started after a warm-up of 24 hours and repeated once after one day to check the level of reproducibility.

The beam used was the sample output of the 126MOPA laser.

The following table resumes all the measured values necessary to compute the M^2 parameter, to show the reproducibility of each measured value.

the $d_1^{(x,y)}$ and $d_2^{(x,y)}$ are the positions where the beam is $\sqrt{2}$ of the waist w_0, which corresponds to the Rayleigh length measured from the waist (the zero is not placed on the waist but near the lens).

[1] the probe is located near to the input of the two chiller hoses and probably 1 inches far from the closest laser diode [1].

Lens	$2w_0^{(x)}$ μm	$2w_0^{(y)}$ μm	$d_1^{(x)}$ mm	$d_2^{(x)}$ mm	$d_1^{(y)}$ mm	$d_2^{(y)}$ mm	M_x^2	M_y^2
KPX106	567.8	436.1	345.0	361.5	740.0	600.0	1.196	1.177
KPX106	566.9	436.6	346.0	361.5	739.0	600.0	1.201	1.178
KPX100	439.9	336.0	226.0	243.5	466.0	383.5	1.190	1.190
KPX100	438.6	334.8	228.0	244.0	465.0	382.5	1.198	1.195
KPX100	439.3	335.8	226.0	243.0	466.0	382.5	1.187	1.193
KPX94	352.2	249.9	42.0	101.0	226.5	177.5	0.998	1.205
Average							1.194	1.187
Std Dev.							0.0058	0.0085

The last measurement has not been considered in the average of $M_{x,y}^2$, because of the accuracy needed on the determination of the Rayleigh length position not easily achievable due to the noise on the measured spot size.

The 5^{th} measurement has been done 26 hour after the others and shows values in good agreement respect to the previous results.

2.2 Beam Profile Fit

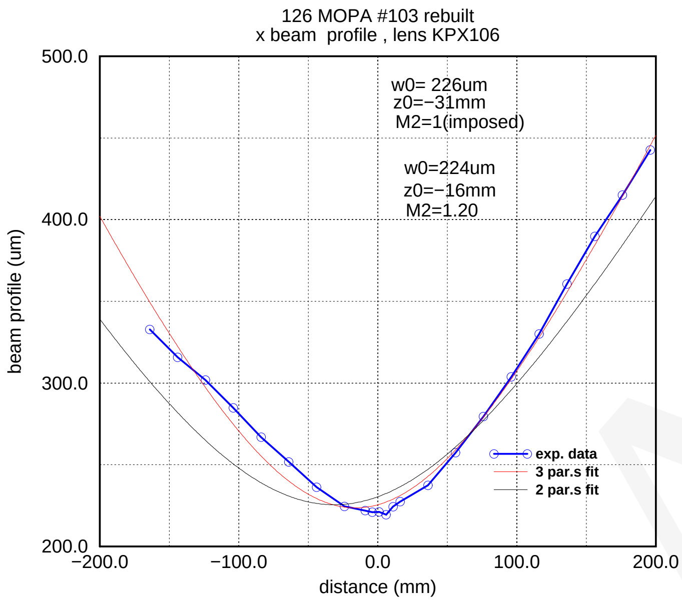
The beam profile has been measured focusing the sample output of the 126MOPA Laser with a Newport lens KPX100 with nominal focal length $f = 150$ mm.

Figures 2.2.a and 2.2.b show the beam profile for the horizontal and vertical directions respectively. The fit using 2 and 3 parameters are also shown on the plots.

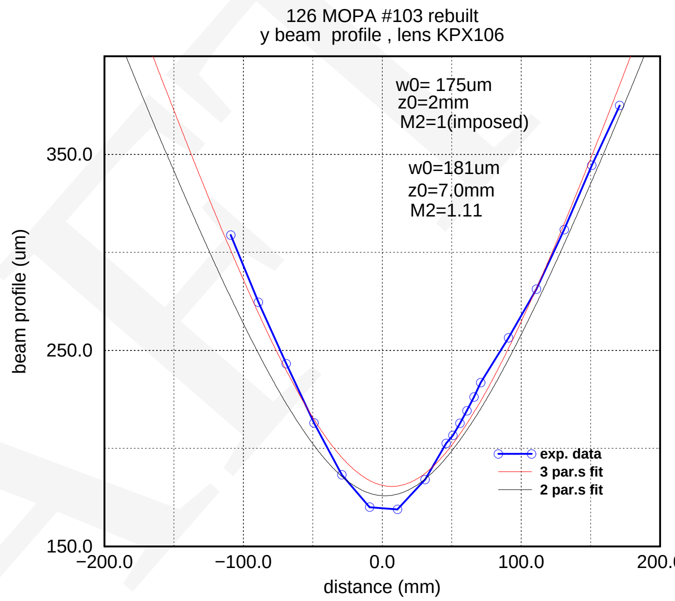
Both profiles show a high asymmetry respect to the waist and not a hyperbolic profile as expected for a Gaussian beam or for an "almost" Gaussian beam.

Consequently, both fits are unable to describe reasonably well the beam profiles because of the asymmetry of the experimental curve (the fitting function is symmetric respect to the origin).

The asymmetry is due essentially to the transverse shape of the beam which is not always symmetric, if measured along the propagation and further, it does not fit in some regions with a Gaussian profile (see figures 2.2 a,b,c,d and 5 a,b,c,d).



a)



b)

Figure 4: Profiles of the focused laser beam of the Lightwave 126MOPA#103R

Conclusions

The $\langle M^2 \rangle$ values measured for horizontal and vertical profiles are out of the specifications given to Lightwave:

$$\sqrt{M_x^2 \cdot M_y^2} < 1.1, \qquad \sqrt{\langle M_x^2 \rangle \cdot \langle M_y^2 \rangle} = 1.19 \tag{3}$$

The beam profile measurement show that the M^2 parameter is not a key parameter for the characterization of the beam profile quality, especially in the case of the 126MOPA#103R.

The asymmetry of the beam profile yields difficult the computation of the beam profile propagation and consequently the mode matching of cavities. In particular it becomes much more critical the correction of the astigmatism of the beam.

3 126MOPA s/n 107 Beam profile

This set of measurements has been done on the last laser delivered by Lightwave.

The total running time at the end of all the measurements was less than 300hours. The temperature of the chiller was 27.5°C, the total laser diodes current 25.00 A and the output power $P_{out} = (9.4 \pm 0.1)$ W.

The laser warm-up time has been specified for all the measurements.

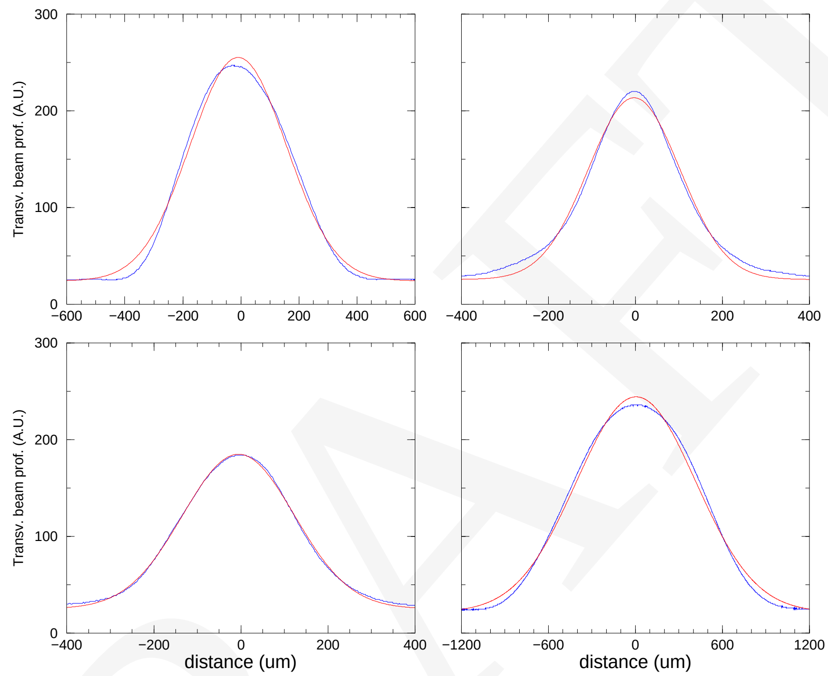


Figure 5: Transverse horizontal profiles and fits of the focused laser beam of the Lightwave 126MOPA#107 along the beam propagation, a) after the lens, b) and c) in the vicinity of the waist and d) in the far field region.

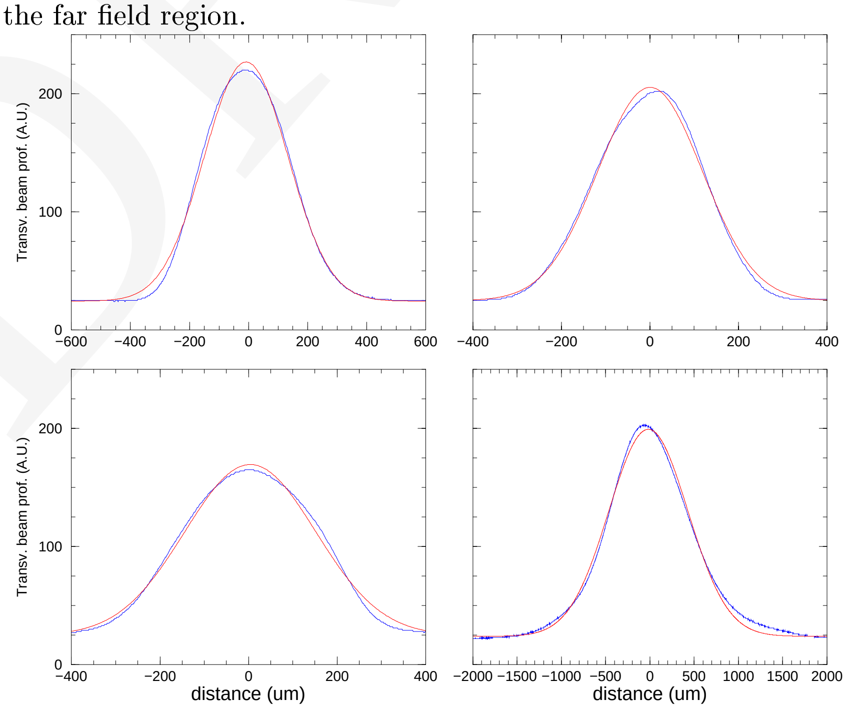


Figure 6: Transverse vertical profiles and fits of the focused laser beam of the Lightwave 126MOPA#107 along the beam propagation, a) after the lens, b) and c) in the vicinity of the waist and d) in the far field region.

3.1 M^2 Measurements

The M^2 parameter measurement for 126MOPA s/n 107 has been performed using the same procedure used for the 126MOPA s/n 107.

The measures has been started after a warm-up of 24 hours and repeated after one day to check the level of reproducibility.

In the following table are resumed all the measured values necessary to compute the parameter to show the reproducibility of each value as pointed out before.

Lens	$2w_0^{(x)}$ μm	$2w_0^{(y)}$ μm	$d_1^{(x)}$ mm	$d_2^{(x)}$ mm	$d_1^{(y)}$ mm	$d_2^{(y)}$ mm	M_x^2	M_y^2
KPX106	667.2	440.1	269.0	886.0	386.5	659.5	1.065	1.047
KPX106	666.3	438.9	273.0	881.0	386.0	659.0	1.080	1.046
KPX106	666.9	439.8	273.0	884.0	387.0	659.0	1.075	1.050
KPX100	423.7	295.5	338.0	594.0	343.5	467.0	1.035	1.044
KPX100	424.4	294.6	338.0	594.0	343.5	466.5	1.039	1.042
KPX100	424.3	294.4	337.5	593.5	353.5	466.5	1.038	1.043
Average							1.055	1.045
Std Dev.							0.020	0.003

The M^2 values computed for the x direction, seem to be strongly dependent on the lens used. This could be explained considering the transverse shape of the beam which is not Gaussian along the propagation axis. So using different focal length the computed Rayleigh length position of a Gaussian beam could be not properly "scaled".

A Second set of measurement done after 72 hours of warm-up has shown a different result on the beam quality and of the beam profile.

Lens	$2w_0^{(x)}$ μm	$2w_0^{(y)}$ μm	$d_1^{(x)}$ mm	$d_2^{(x)}$ mm	$d_1^{(y)}$ mm	$d_2^{(y)}$ mm	M_x^2	M_y^2
KPX100	514.4	346.5	169.5	514.5	254.5	412.5	1.132	1.122
KPX100	514.0	343.0	170.0	514.5	256.5	411.5	1.132	1.121
KPX100	515.9	341.1	168.0	516.0	257.0	411.5	1.129	1.112
Average							1.131	1.118
Std Dev.							0.002	0.006

This different results on the M^2 values, are due to the instability of the beam profile, which has been erroneously supposed stable, after a warm-up of 24 hours. The beam profile stability needs to be investigated.

Conclusions

Considering the first set of measurement The $\langle M^2 \rangle$ values measured for horizontal and vertical profiles fulfill the specification:

$$\sqrt{M_x^2 \cdot M_y^2} < 1.1, \qquad \sqrt{\langle M_x^2 \rangle \cdot \left\langle M_y^2 \right\rangle} = 1.050 \tag{4}$$

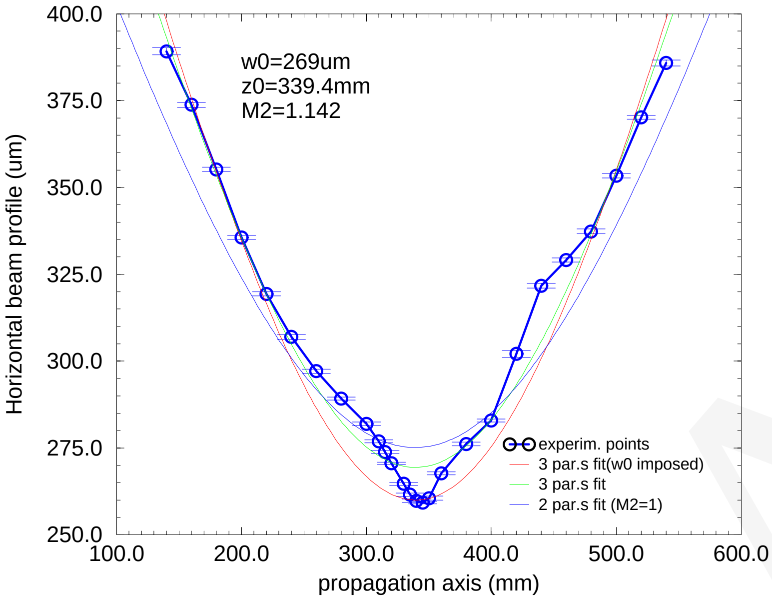
The second set of measurements (performed after the longer warm-up), gives the opposite following result:

$$\sqrt{\langle M_x^2 \rangle \cdot \left\langle M_y^2 \right\rangle} = 1.12 \tag{5}$$

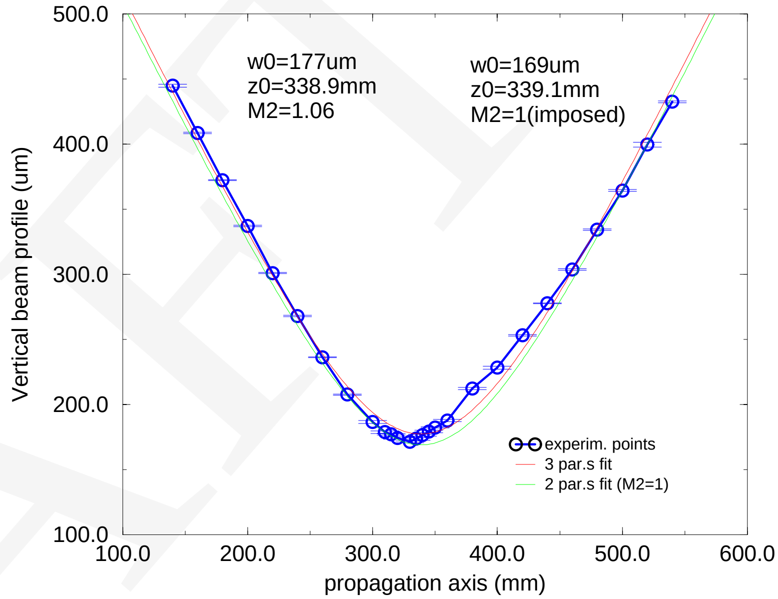
Anyway, a qualitative comparison of the transverse beam profiles between the 126MOPA103R and this laser, confirm the doubt on the validity of the M^2 parameter as good estimator of the transverse beam mode purity (the beam with the worst profile has an M^2 better than that with a better Gaussian profile).

3.2 Beam Profile Fit

The beam profile has been measured focusing the sample output of the 126MOPA Laser with a Newport lens KPX100.



a)



b)

Figure 7: Profiles of the focused laser beam of the Lightwave 126MOPA#107

Figures 3.2.a and 3.2.b show the beam profile for the horizontal and vertical directions respectively. The fit using 2 and 3 parameters are shown on the plots.

The horizontal profile presents large deviations from a hyperbolic function and therefore the fits are not able to describe reasonably well the trend of the experimental points. This deviation is clearly visible considering the horizontal transverse profile of the beam which does not fit with a Gaussian profile (see figures 3.2a,b,c,d).

The vertical profile shows less problems and the both the 2 and 3 parameter fit give a satisfying result. Anyway a slight asymmetry of the polygonal of the experimental points is visible if compared with the fits curves.

4 Profile Stability

The stability of the profile during a period needed to perform the measurements (about 1 hour), has been investigated to verify the presence of any systematic errors.

The beam used for the tests was the sample beam.

Long term stability has not been deeply tested.

4.1 126MOPA#104

The only test available for this laser and for relatively long term stability is a continuous monitoring of the beam diameter for 8.5 hours of the laser 126MOPA#104 after a warm-up of 3 days. The figure 10, shows the beam diameter drift on the horizontal and vertical directions.

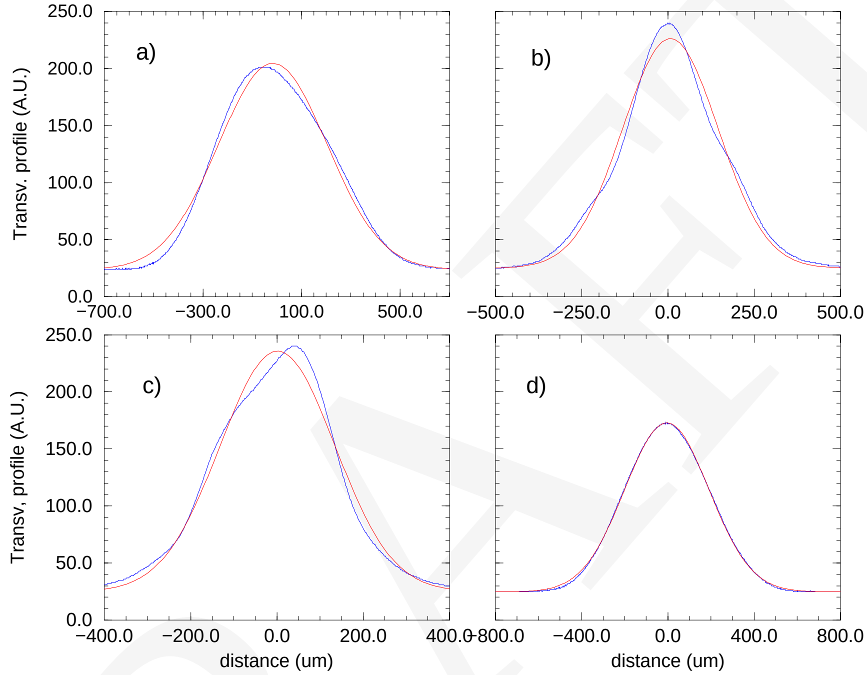


Figure 8: Transverse horizontal profiles and fits of the focused laser beam of the Lightwave 126MOPA#107 along the beam propagation, a) after the lens, b) and c) in the vicinity of the waist and d) in the far field region.

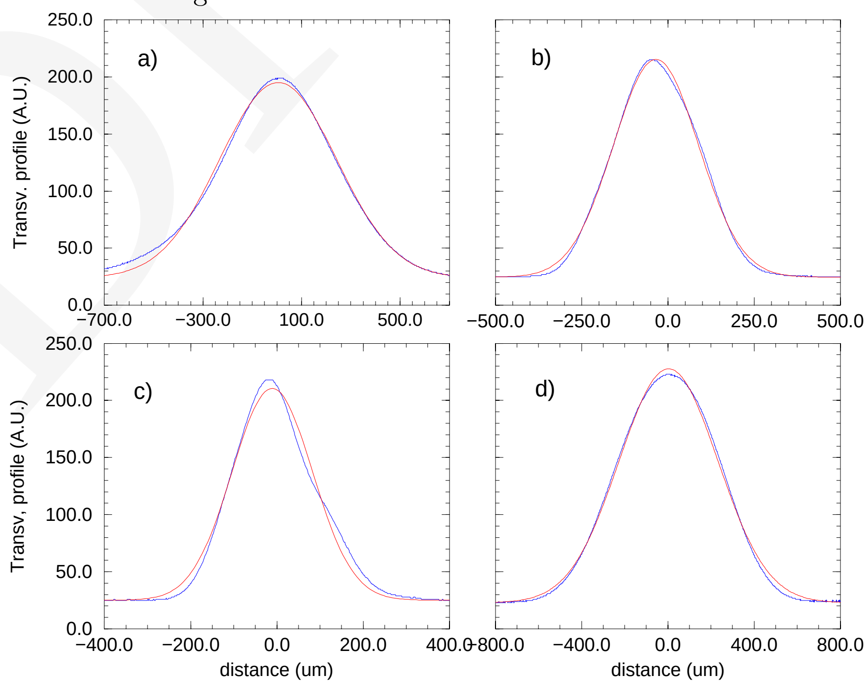


Figure 9: Transverse vertical profiles and fits of the focused laser beam of the Lightwave 126MOPA#107 along the beam propagation, a) after the lens, b) and c) in the vicinity of the waist and d) in the far field region.

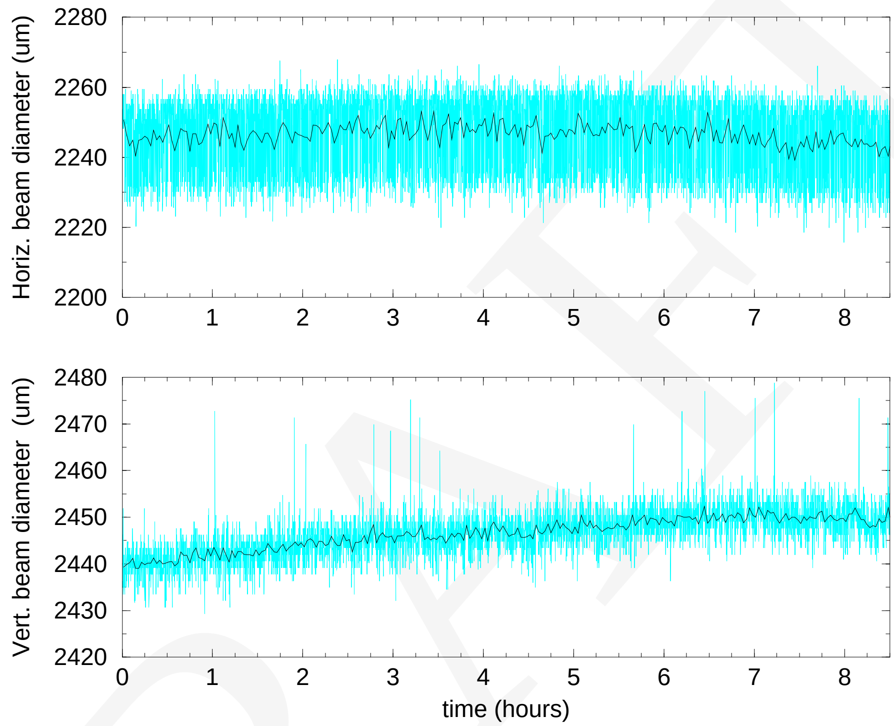


Figure 10: Beam diameter versus time for the 126MOPA#104.The dark lines are the averages of "raw" data.

The dark line has been obtained averaging the noisier signal shown in the background. The laser power was $P_{out} = (11.1 \pm 0.1)$ W and stable within about 1%.

4.2 127MOPA#107

The figure 11, shows the vertical and horizontal beam diameter D_x D_y versus time for a period of about 1 hour of the laser #107.

The data has been taken at a rate of 5 samples/sec and averaged with a time period of 8 sec.

The relative diameter beam fluctuations are

$$\frac{\Delta D_x}{\langle D_x \rangle} = 0.2\%, \qquad \frac{\Delta D_y}{\langle D_y \rangle} = 0.5\% \tag{6}$$

which are about the same order of magnitude of the relative error on the beam size measurements done to study the beam profile and therefore reasonably negligible.

The 127MOPA#107 beam profile stability has been tested during a period of 3 days as shown in figure 10. Due to the quick setup for the test, only the beam diameter has been continuously monitored.

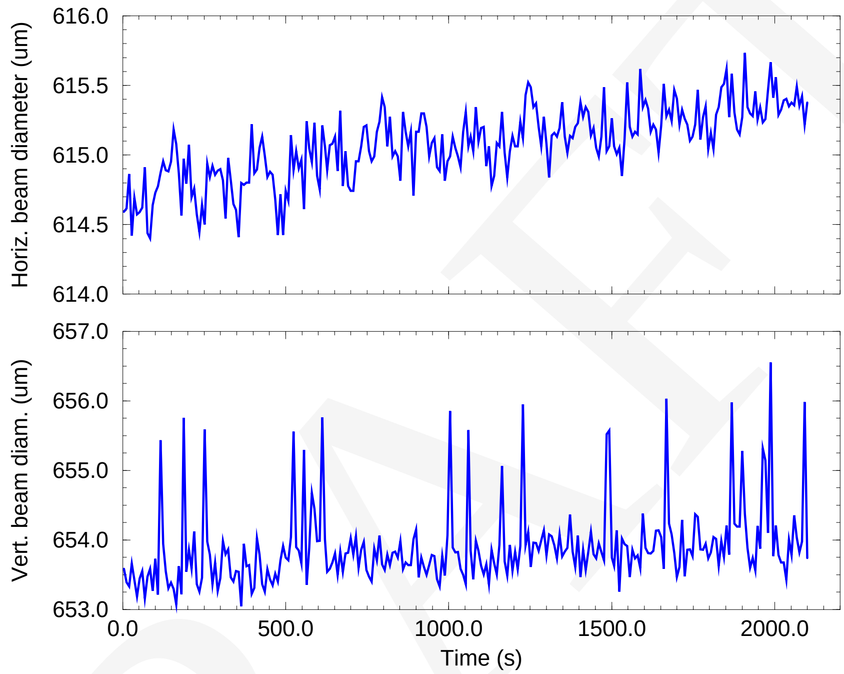


Figure 11: Beam diameter versus time for the 126MOPA#107.

The warm-up period was longer than 4 days and no lenses has been used to focus the sample beam. The laser power was $P_{out} = (9.3 \pm 0.1)$ W and stable within about 1%.

The figure 12, shows the beam diameter drift on the horizontal and vertical directions. The dark line has been obtained averaging the noisier signal shown in the background.

the beam size has been sampled at a frequency of 20 values per minute (bright signal on the figure 12) and averaged for a period of 5 minutes (the dark signal).

The relative diameter beam fluctuations for long periods are

$$\frac{\Delta D_x}{\langle D_x \rangle} \simeq 0.7\%, \qquad \frac{\Delta D_y}{\langle D_y \rangle} \simeq 0.5\%. \tag{7}$$

The asymmetry of the average signal respect to the noise range, clearly visible on the figure 12, is due to the non-visible spikes in the noisier signal.

References

[1] Glen Truong, Lightwave, private communication.

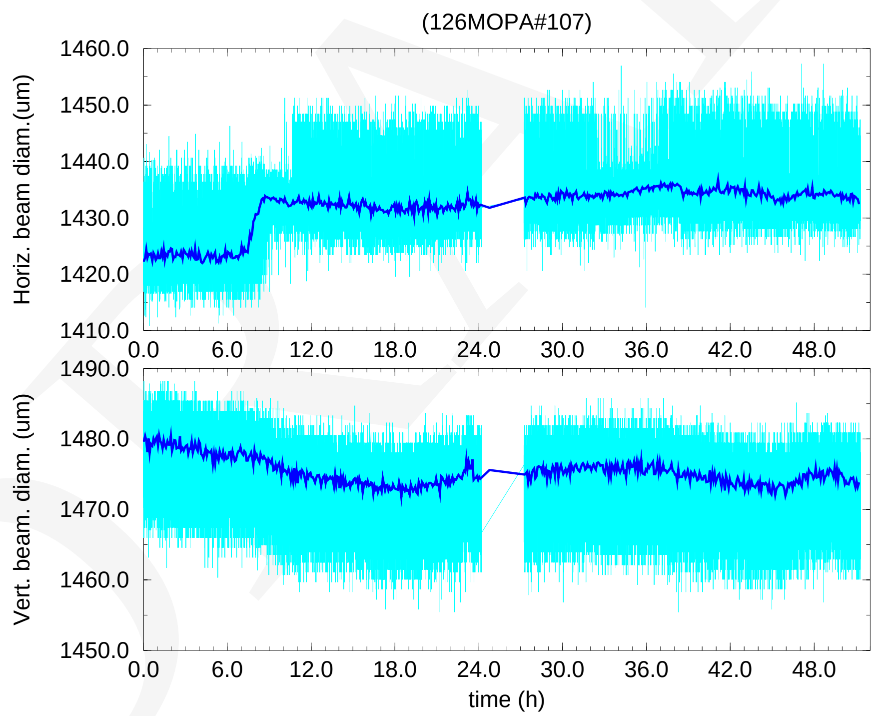


Figure 12: Beam diameter versus time for the 126MOPA#104.The dark lines are the averages of "raw" data. The "blank zone" is an interruption of the data acquisition for about 3 hours. The spikes on the signals are not visible due to their to high density.