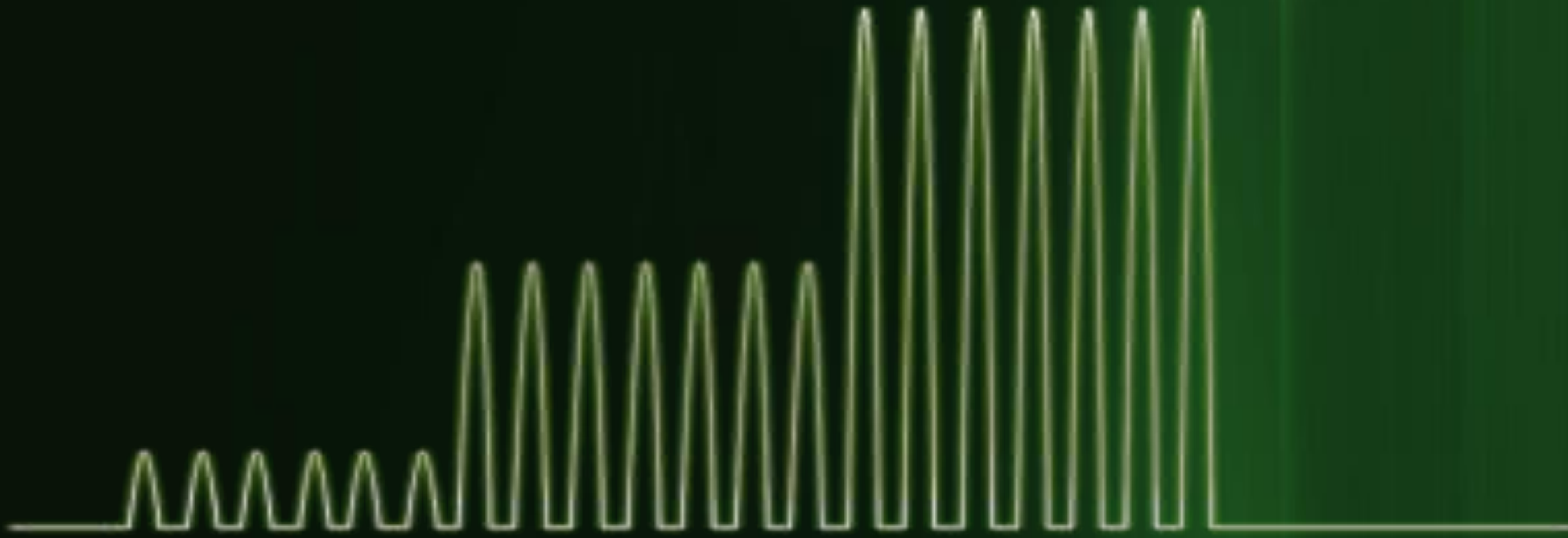
Nufern, East Granby, CT, USA

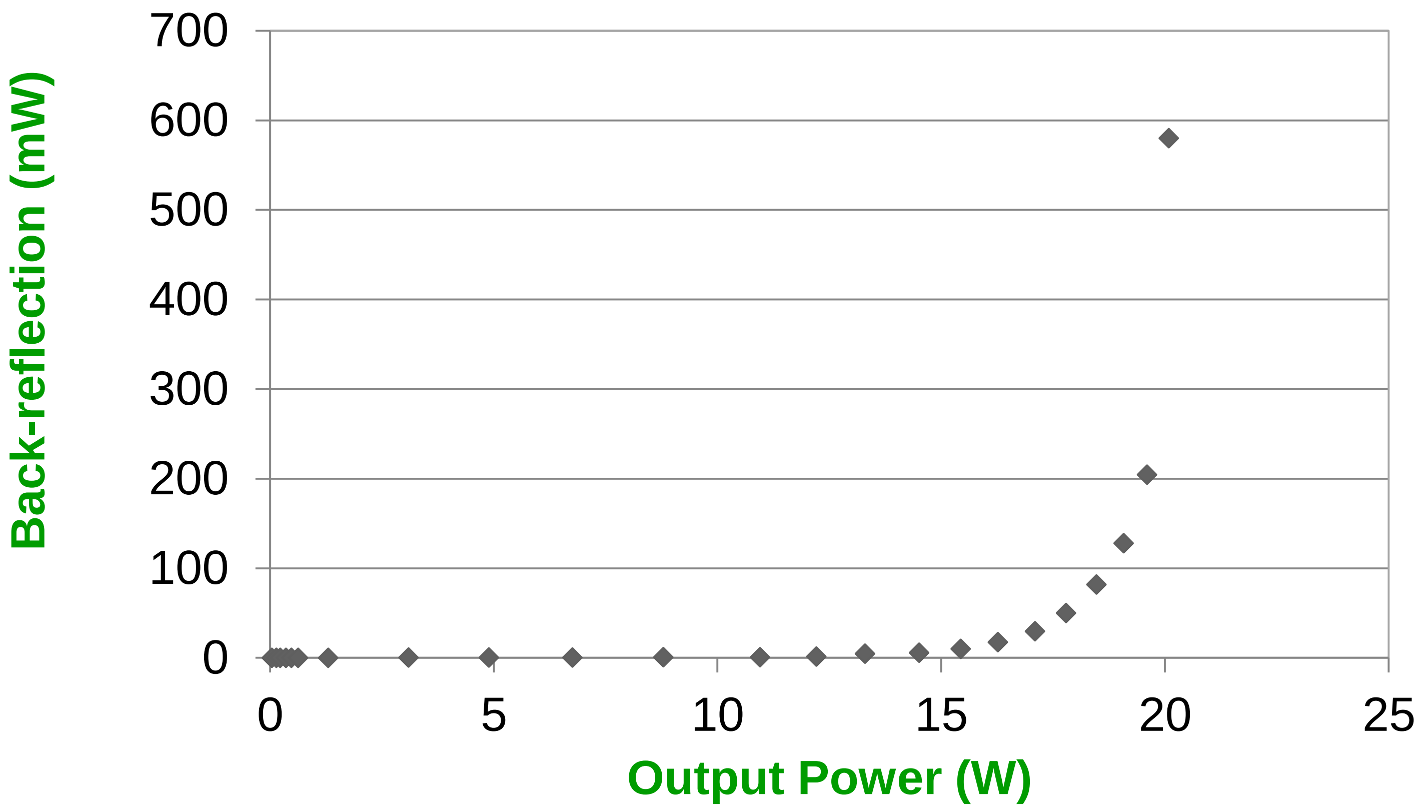
Progress on High Power Single Frequency Fiber Amplifiers at 1μm, 1.5μm and 2μm

www.nufern.com



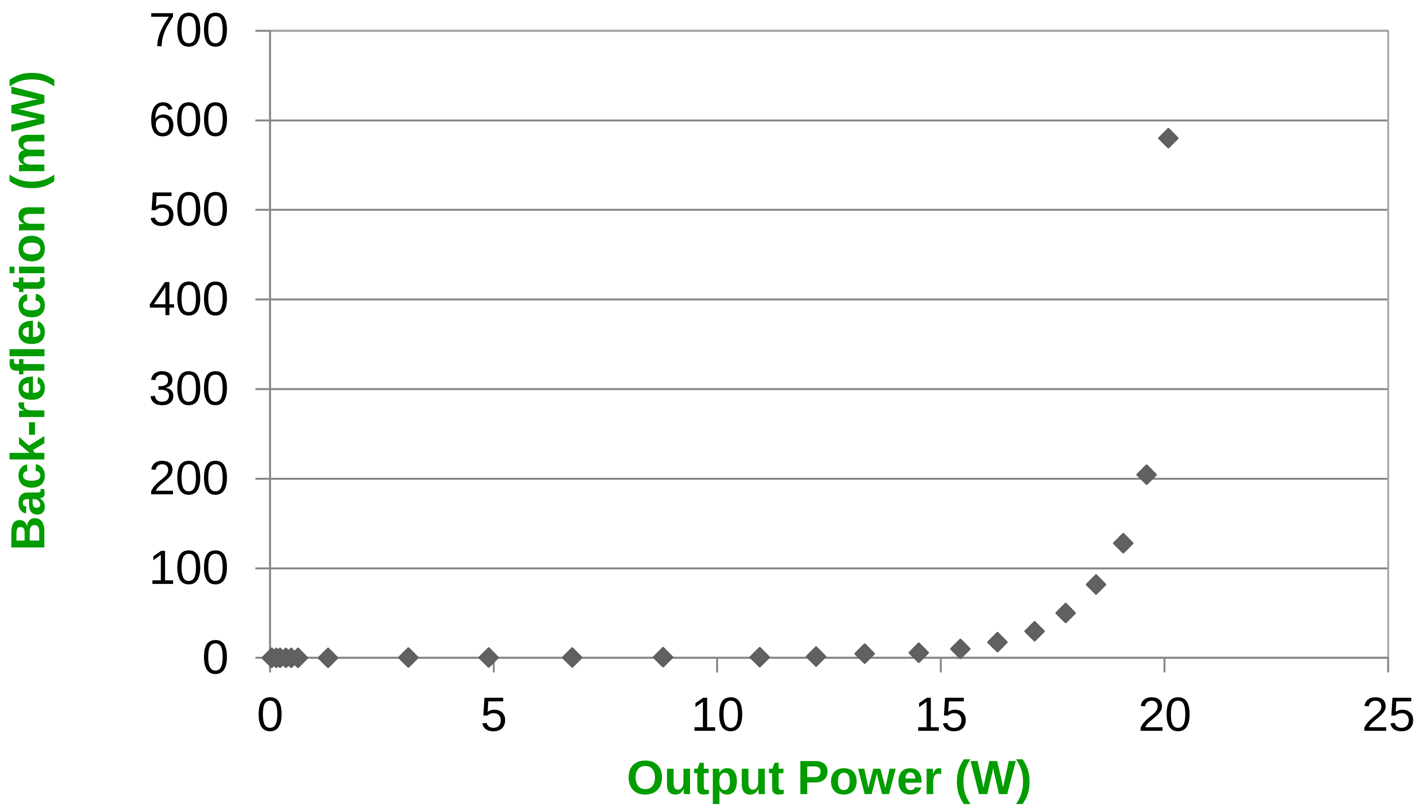
Examples of Single Frequency Platforms at 1μm and 1.5μm and Applications

Single Frequency PM Amplifier Platform (2-15W)



SBS threshold at 1064nm in 6.5m PLMA-YDF-10125
with 3m PM-DSF-10/125 delivery fiber on output

Single Frequency PM Amplifier Platform (2-15W)



Practical SBS limit in current generation of **PM single mode Yb and Er:Yb** multi-stage amplifiers is ~20W (15W) at 1µm (1.5µm)

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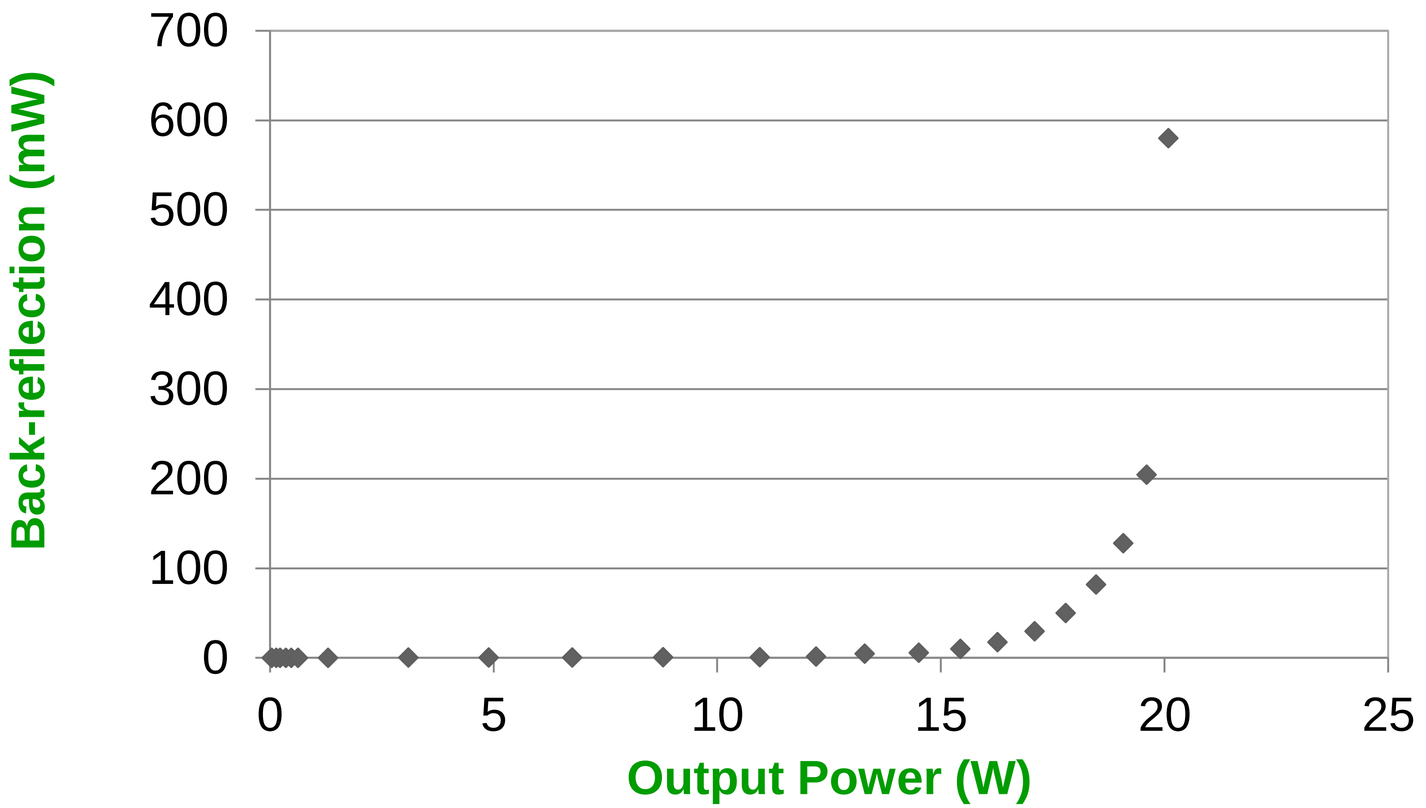
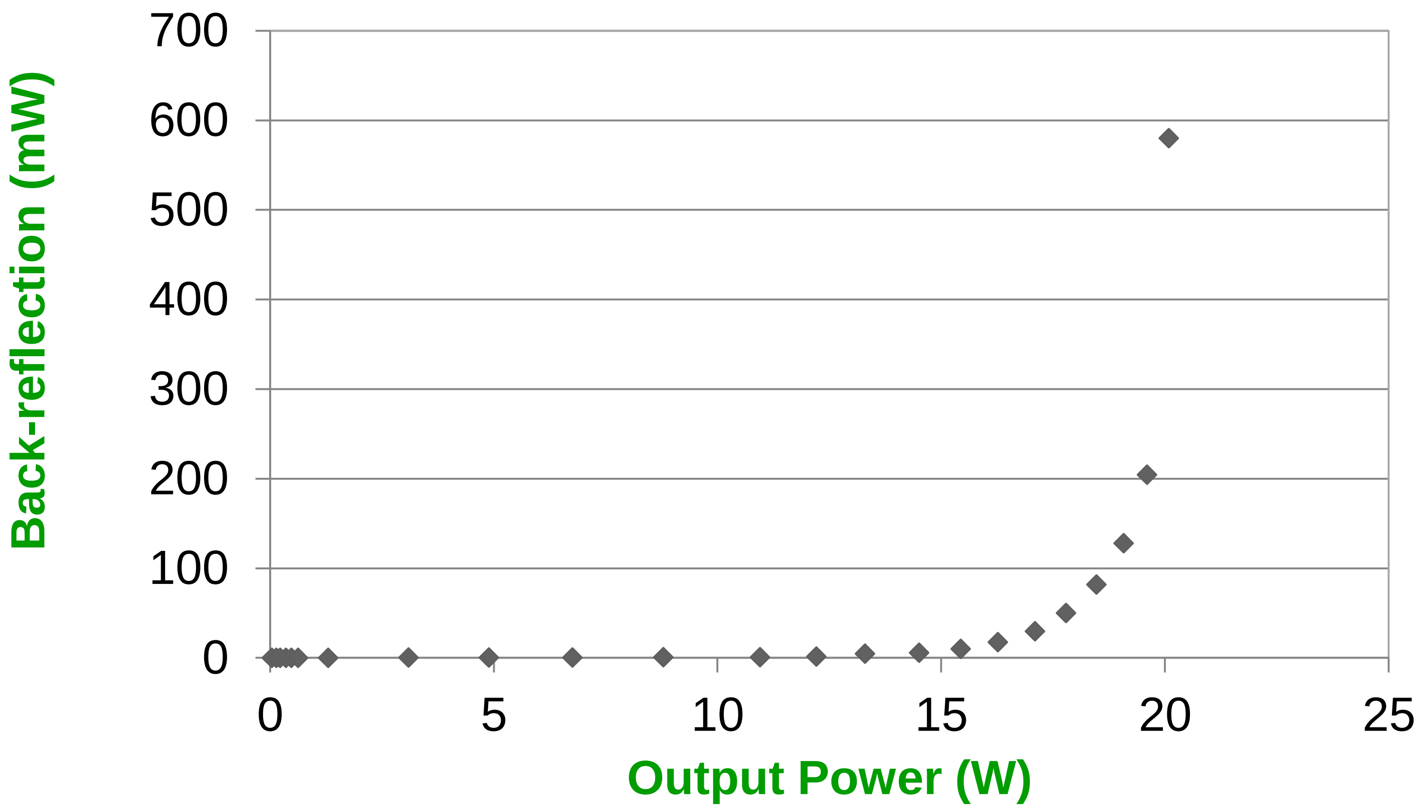
Single Frequency PM Amplifier Platform (2-15W)



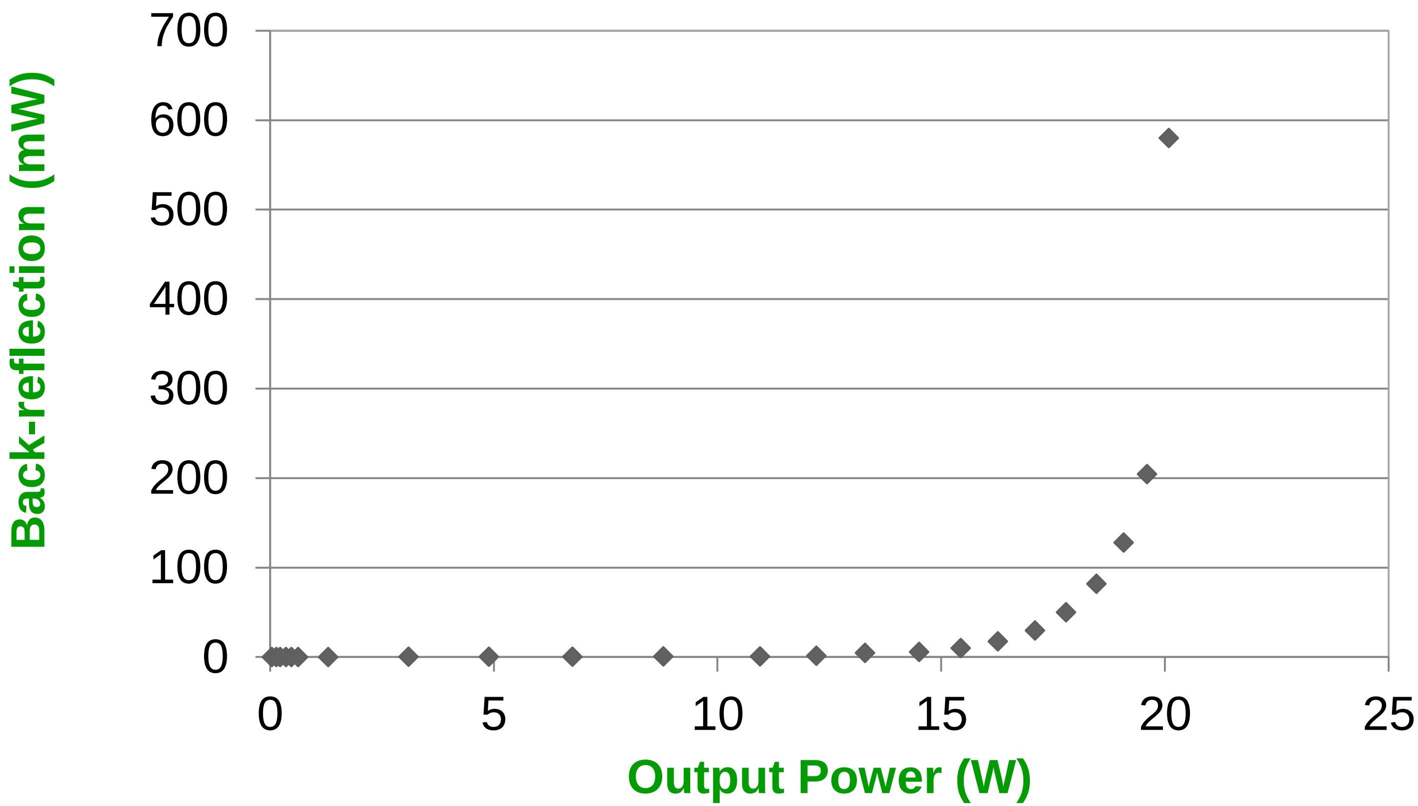
Standard wavelengths 1060-1085nm and 1540-1560nm

Single Frequency PM Amplifier Platform (2-15W)



Multiple options available (isolation, control, input power, etc)

Single Frequency PM Amplifier Platform (2-15W)



Mature platform, more than 50 amplifiers delivered over last 4 years

Single Frequency PM Amplifier Platform (2-15W)

Demo models available for evaluation

Specially designed Yb doped fibers with increased mode filed diameter but maintaining single mode spatial beam profile were used to alleviate the SBS limitation.

Single Frequency PM Amplifier Platform (2-15W)

Demo models available for evaluation

SBS-suppression fibers were used to further decrease the SBS threshold.

Single Frequency PM Amplifier Platform (2-15W) Optical Specifications

Optical Specification[1]	NUA-UUUU-PV-0002-YZ	NUA-UUUU-PV-0005-YZ	NUA-UUUU-PV-0010-YZ	NUA-UUUU-PV-0015-YZ
Output Power	2.0 W	5.0 W	10.0 W	15.0 W*
Output Power Adjustment (nominal)	10–100%	10–100%	10–100%	10–100%
Power Stability[2]	≤ 3.0%	≤ 3.0%	≤ 3.0%	≤ 3.0%
Mode	TEM_{00}	TEM_{00}	TEM_{00}	TEM_{00}
Output Type	No isolator, FC/APC connector	No isolator, FC/APC connector	No isolator, FC/APC connector	No isolator, FC/APC connector
	Fiber to fiber Isolator, FC/APC connector	Fiber to fiber Isolator, FC/APC connector	Fiber to fiber Isolator, FC/APC connector	
	Fiber to free space isolator	Fiber to free space isolator	Fiber to free space isolator	Fiber to free space isolator
Input Type	FC/APC bulkhead	FC/APC bulkhead	FC/APC bulkhead	FC/APC bulkhead
Mode of Operation	CW	CW	CW	CW
Polarization	Linear	Linear	Linear	Linear
PER at Rated Power[3]	≥ 15 dB	≥ 15 dB	≥ 15 dB	≥ 15 dB
Operating Wavelength	1064 – 1083 nm	1064 – 1083 nm	1064 – 1083 nm	1064 – 1083 nm
	1084 – 1100 nm	1084 – 1100 nm	1084 – 1100 nm	1084 – 1100 nm
	1100 – 1110 nm	1100 – 1110 nm	NA	NA
Signal Input Power	1.0–15.0 mW	1.0–15.0 mW	1.0–15.0 mW	1.0–15.0 mW
	15.0 – 50.0 mW	15.0 – 50.0 mW	15.0 – 50.0 mW	15.0 – 50.0 mW
	50.0 – 200.0 mW	50.0 – 200.0 mW	50.0 – 200.0 mW	50.0 – 200.0 mW
Signal Input Isolation	≥ 30 dB	≥ 30 dB	≥ 30 dB	≥ 30 dB
Input Signal Linewidth	≤ 10.0 kHz	≤ 10.0 kHz	≤ 10.0 kHz	≤ 10.0 kHz

Single Frequency PM Amplifier Platform (2-15W) Mechanical, Electrical &Environmental Specifications

	NUA-UUUU-PV-0002-YZ	NUA-UUUU-PV-0005-YZ	NUA-UUUU-PV-0010-YZ	NUA-UUUU-PV-0015-YZ
Mechanical Specifications				
Delivery Fiber Length	1 m	1 m	1 m	1 m
Output Cable Type	Armored cable	Armored cable	Armored cable	Armored cable
Dimensions[4]	275 x 250 x 37 mm	275 x 250 x 37 mm	275 x 250 x 37 mm	275 x 250 x 37 mm
Cold Plate Dimentions	305 x 178 x 14 mm	305 x 178 x 14 mm	305 x 178 x 14 mm	305 x 178 x 14 mm
Weight	3.9 kg	3.9 kg	3.9 kg	3.9 kg
Electrical Specifications				
DC Supply Voltage	24 VDC	24 VDC	24 VDC	24 VDC
Current Consumption	2.0 A	3.0 A	4.0 A	5.0 A
Digital Interfaces	NuCONTROL	NuCONTROL	NuCONTROL	NuCONTROL
Environmental Specifications				
Cooling	Water cooled cold plate	Water cooled cold plate	Water cooled cold plate	Water cooled cold plate

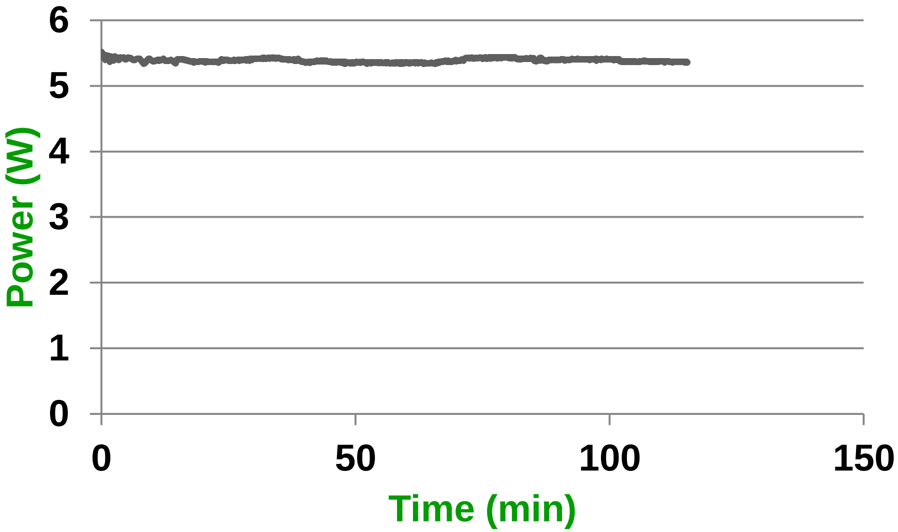
[1] *All specifications are at RT and proper heatsinking is required.*

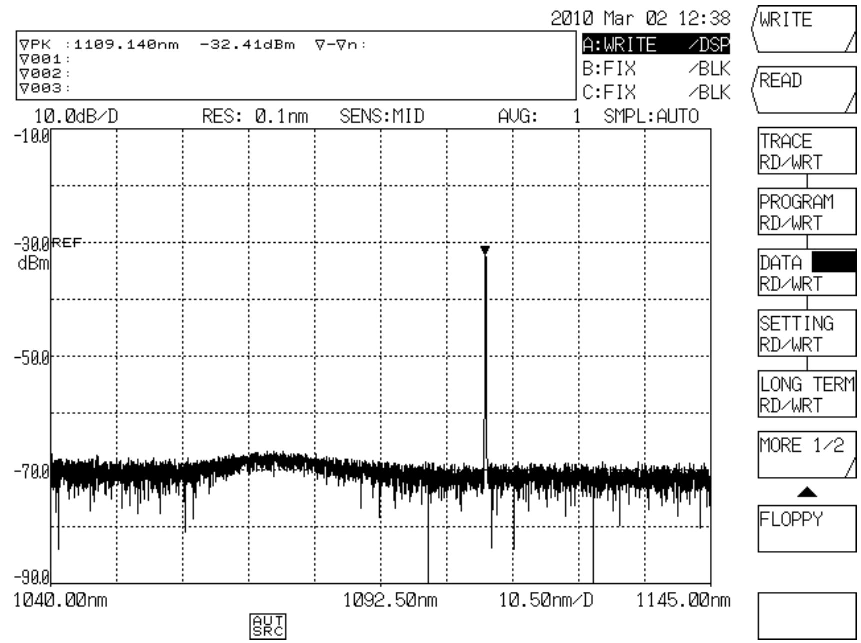
[2] *Stability is measured over 2-hour period & calculated using (max-min)/Avg.*

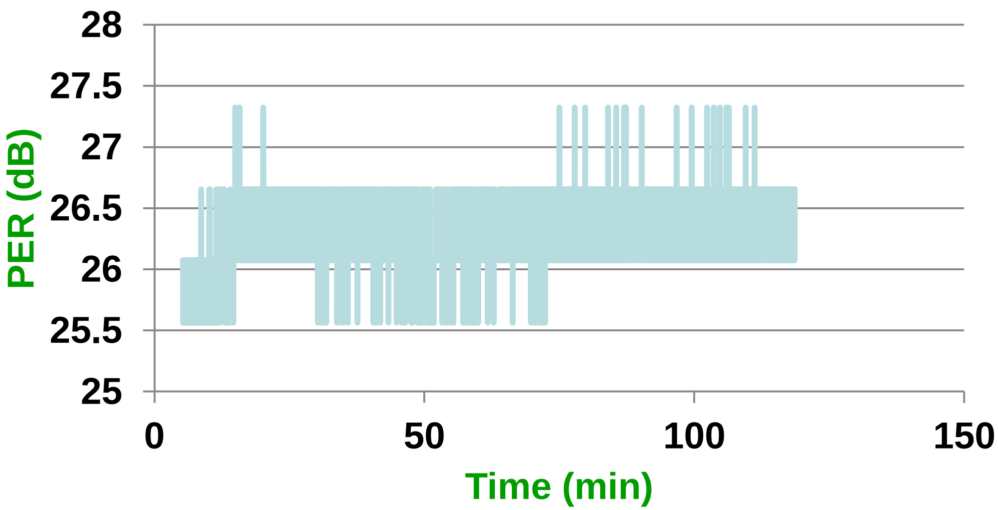
[3] *Measured with isolator*

[4] *Custom OEM packaging available on request.*

Extended Wavelengths Using Yb-doped Fibers

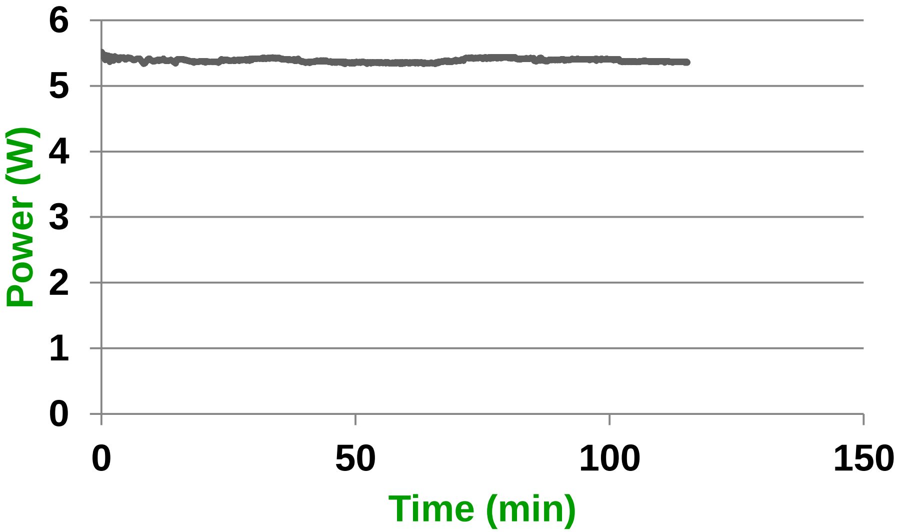


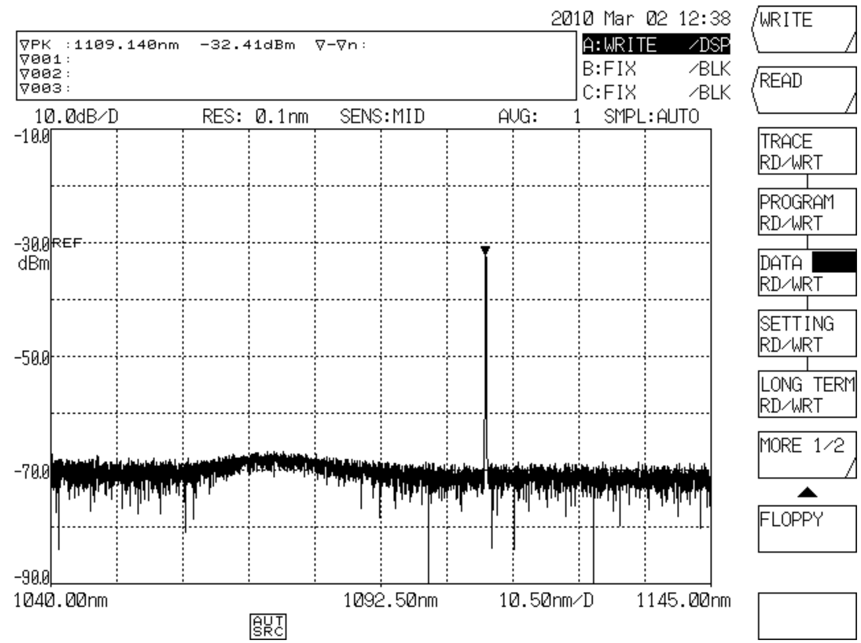


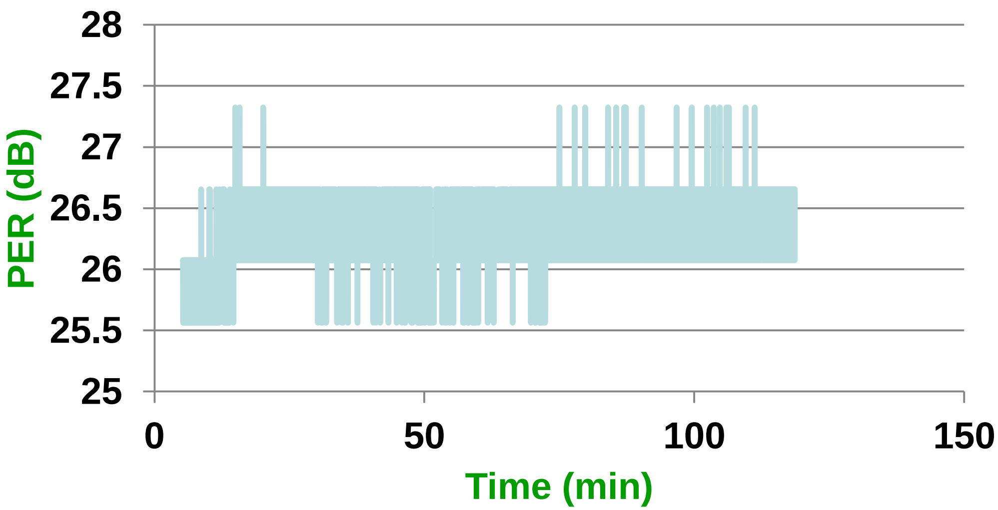


5W 1106nm SFA with a fiber to free space isolator, tested with 1MHz DFB diode

Extended Wavelengths Using Yb-doped Fibers

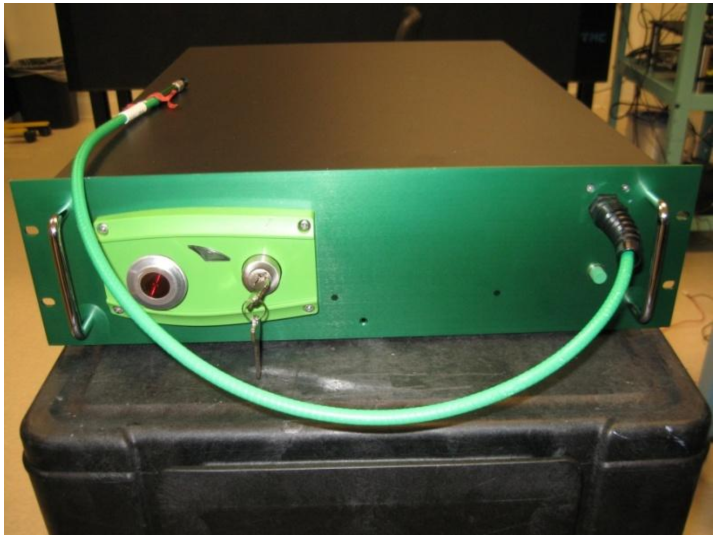




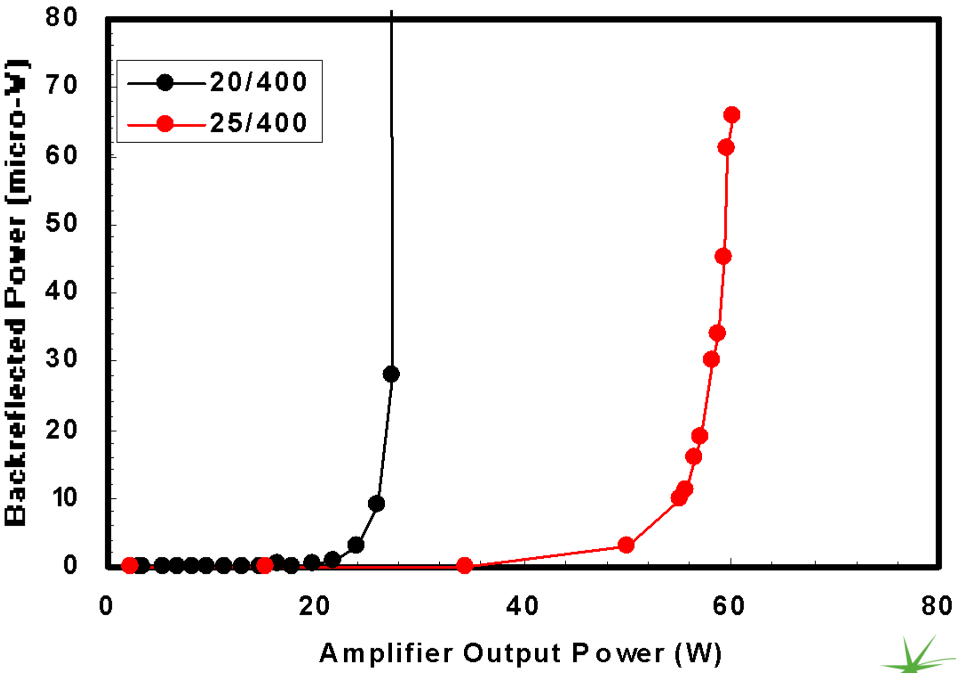


SNR of the SFA operating at 1109nm

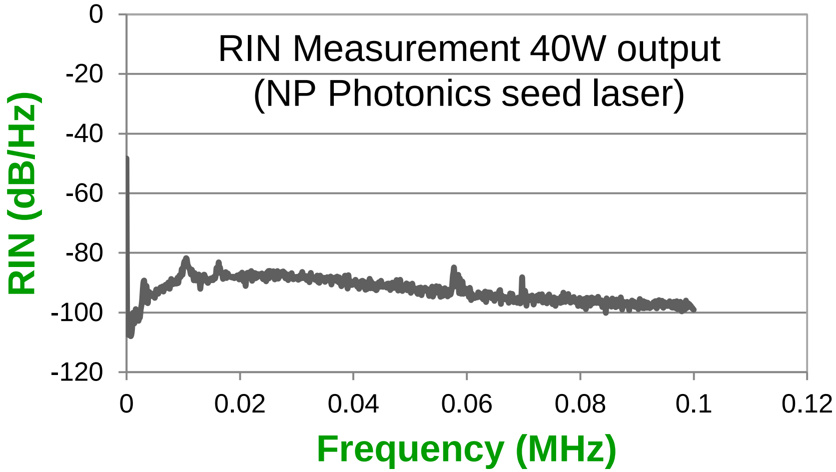
Single Frequency PM Amplifier Platform (40W at 1μm)

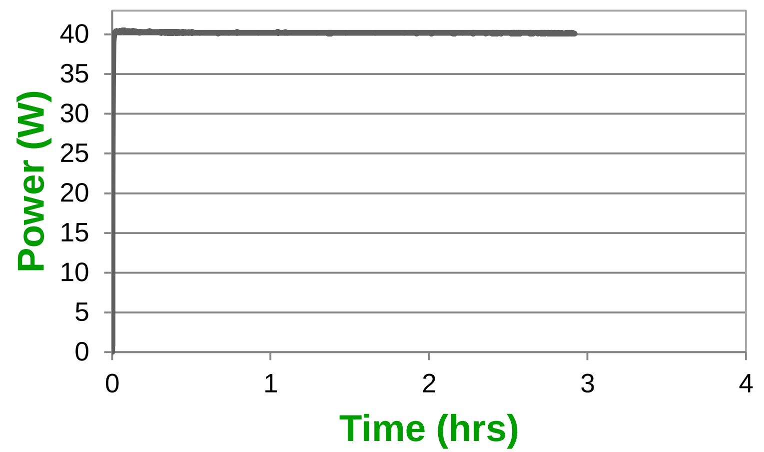


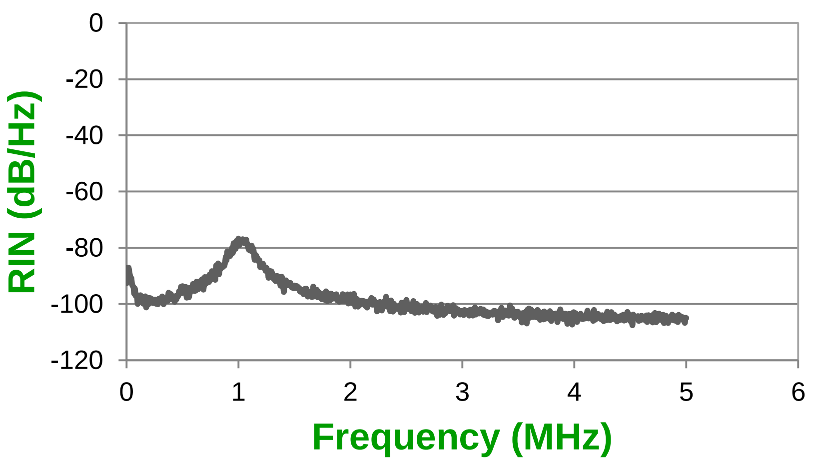
By adopting state of the art PM LMA (25/400) fibers the SBS threshold can be raised to >40W (at 1μm) with 5kHz seed source

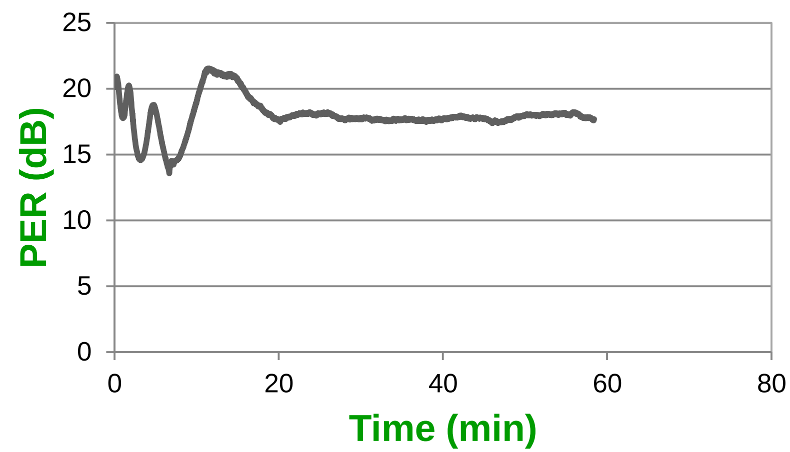


Single Frequency PM Amplifier Platform (40W at 1μm)



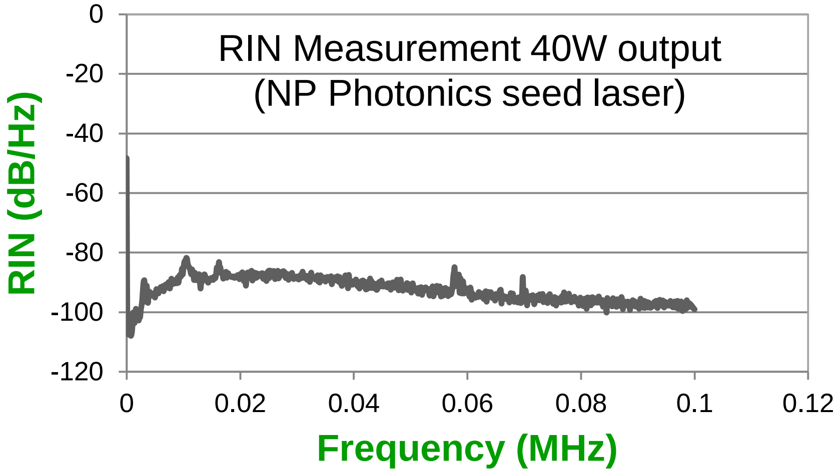


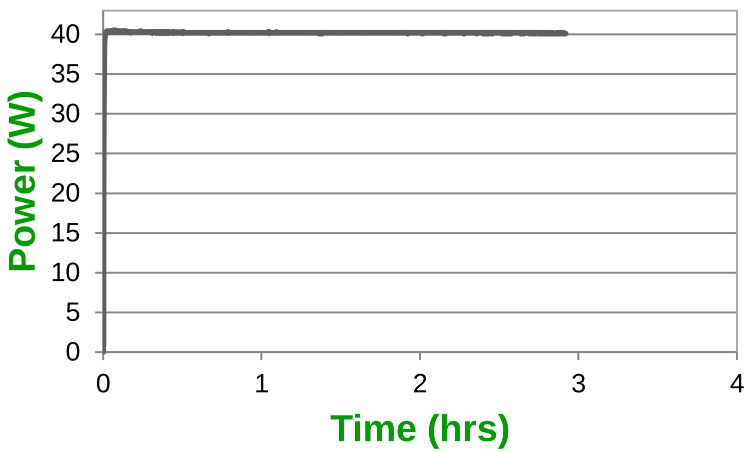


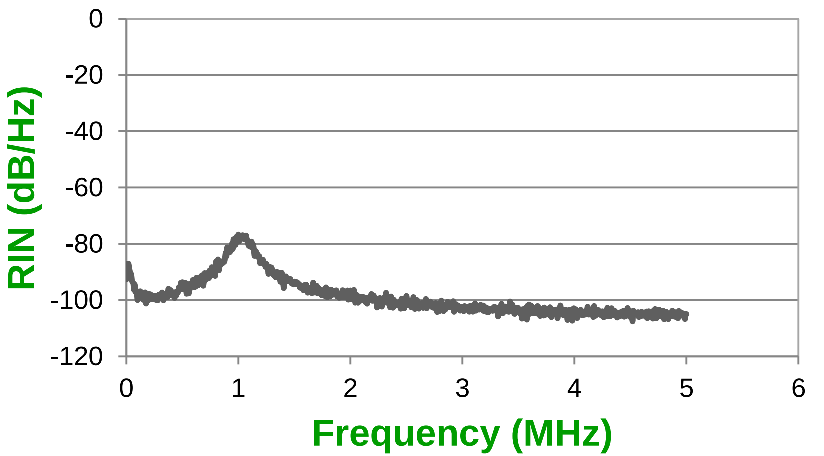


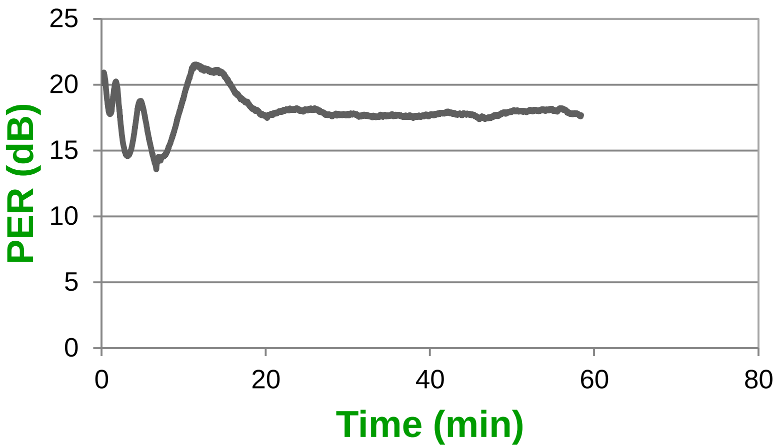
The 40W amplifier platform is fairly new (~8 units delivered in 2009)

Single Frequency PM Amplifier Platform (40W at 1μm)



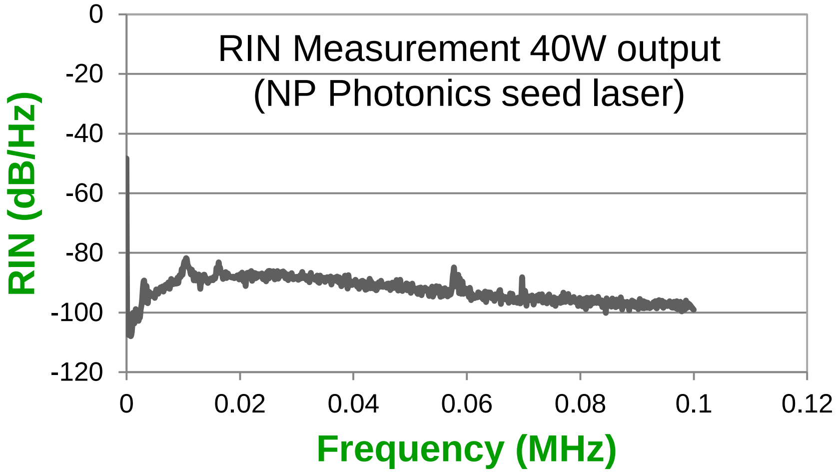


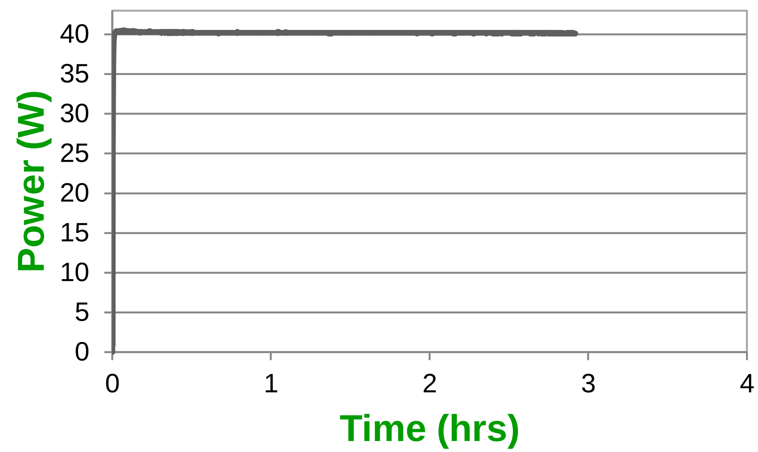


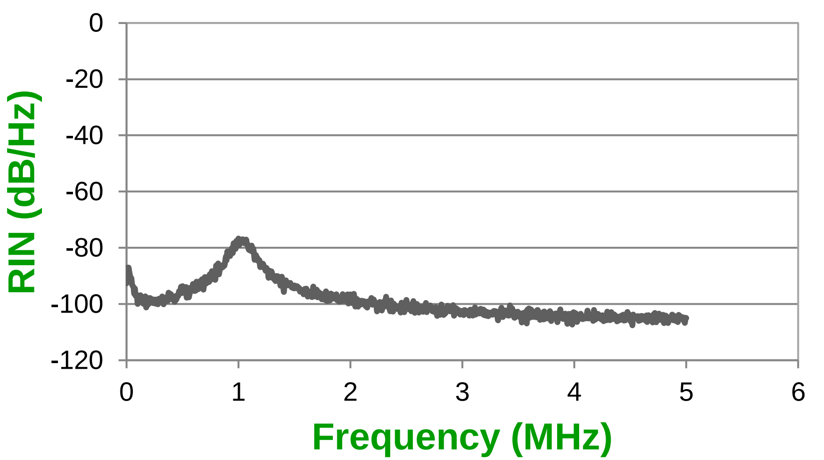


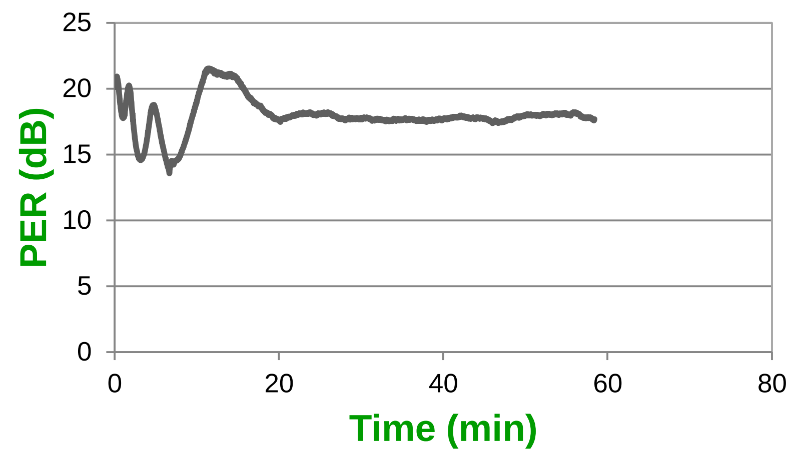
3 systems are under evaluation at MIT (centre of ultra cold atoms)

Single Frequency PM Amplifier Platform (40W at 1μm)



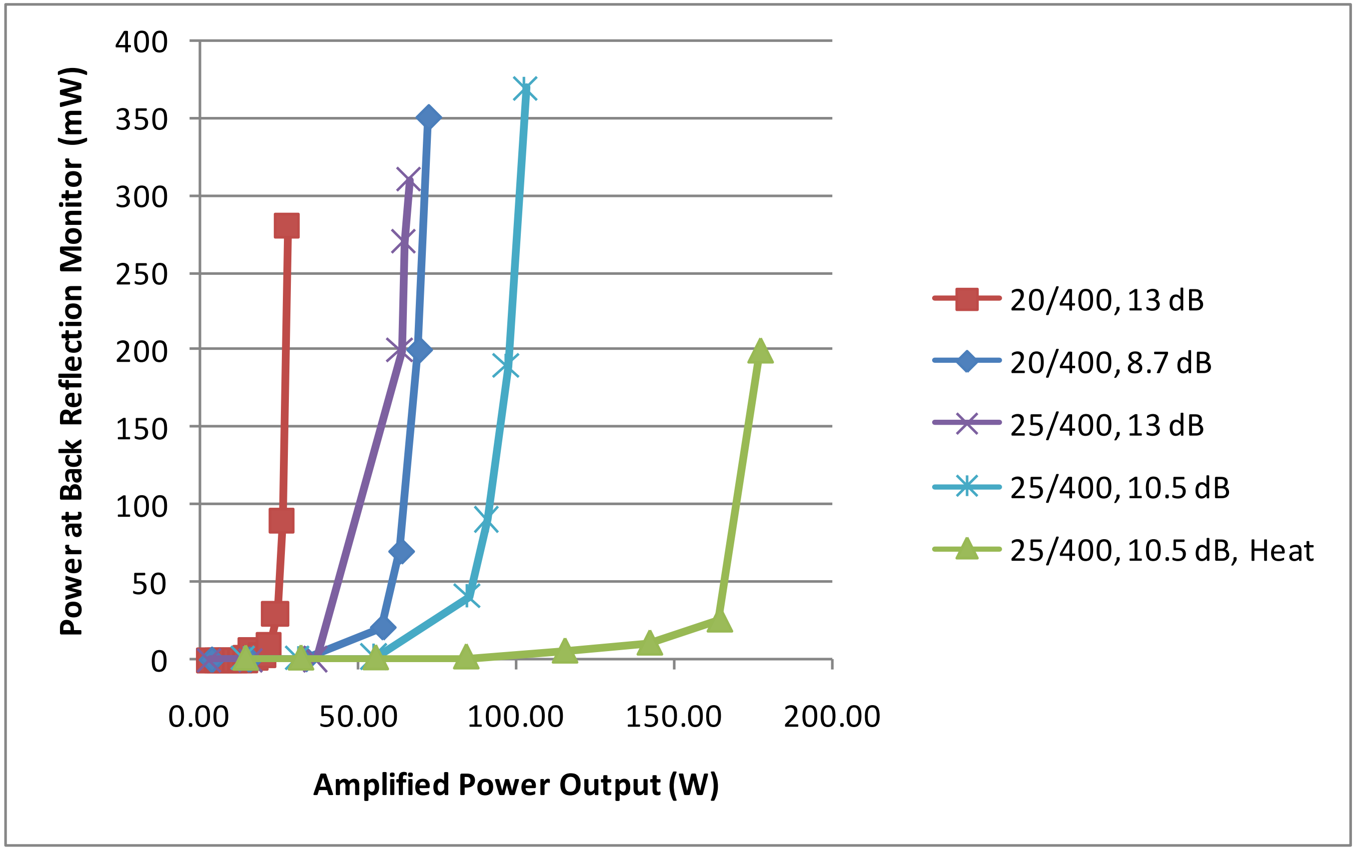






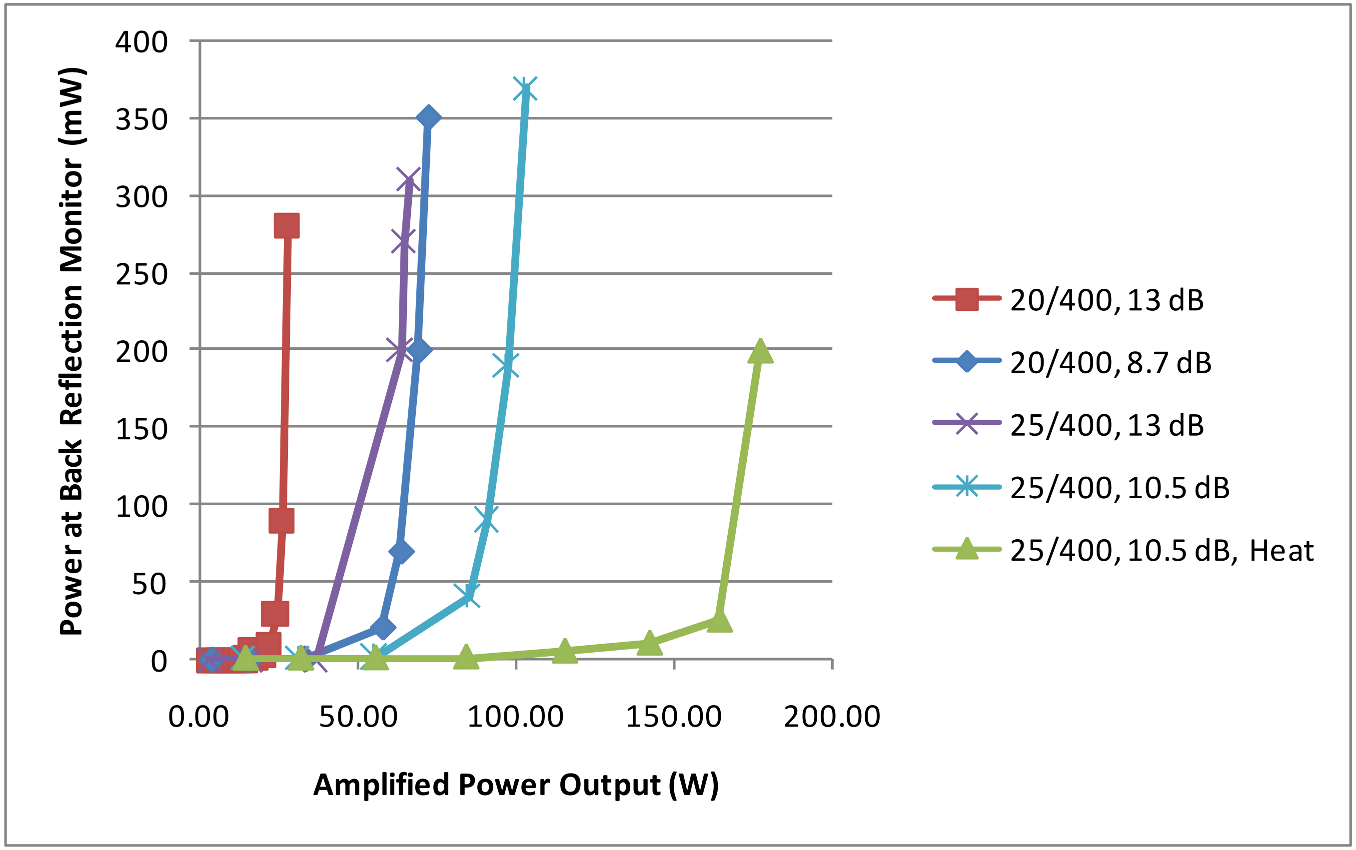
Contact apeyman@mit.edu for references on how the amps are working

Single Frequency PM Amplifier Platform (100W at 1mm)



Practical SBS limit is increased in these PM LMA based amplifiers by using a temperature gradient along the active fiber length

Single Frequency PM Amplifier Platform (100W at 1mm)



Temperature gradient shifts the local SBS gain spectrum along the fiber length

Single Frequency PM Amplifier Platform (100W at 1mm)

Amp Measured Parameters

Property	Tested Value
Output Power [~5kHz]	105.5 W
PER	>15.5 dB
M^2	<1.10
Wavelength	1064.4 nm
Input Power	~ 33mW
Max Backward Power	< 25mW

Single Frequency PM Amplifier Platform (100W at 1mm)

POWER with Oven Off

I_{3A} [A]	I_{3B} [A]	P_{SIGNAL} [W]	P_{BACK} [mW]
10		10.4	0.25
20		33.0	0.55
30		61.1	23.0

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Single Frequency PM Amplifier Platform (100W at 1mm)

POWER with Oven On

I_{3A} [A]	I_{3B} [A]	P_{SIGNAL} [W]	P_{BACK} [mW]
10	0	10.4	0.65
20	0	33.0	0.70
30	0	61.1	0.85
40	0	87.0	4.1
40	10	94.1	6.0
40	15	103.0	17.0

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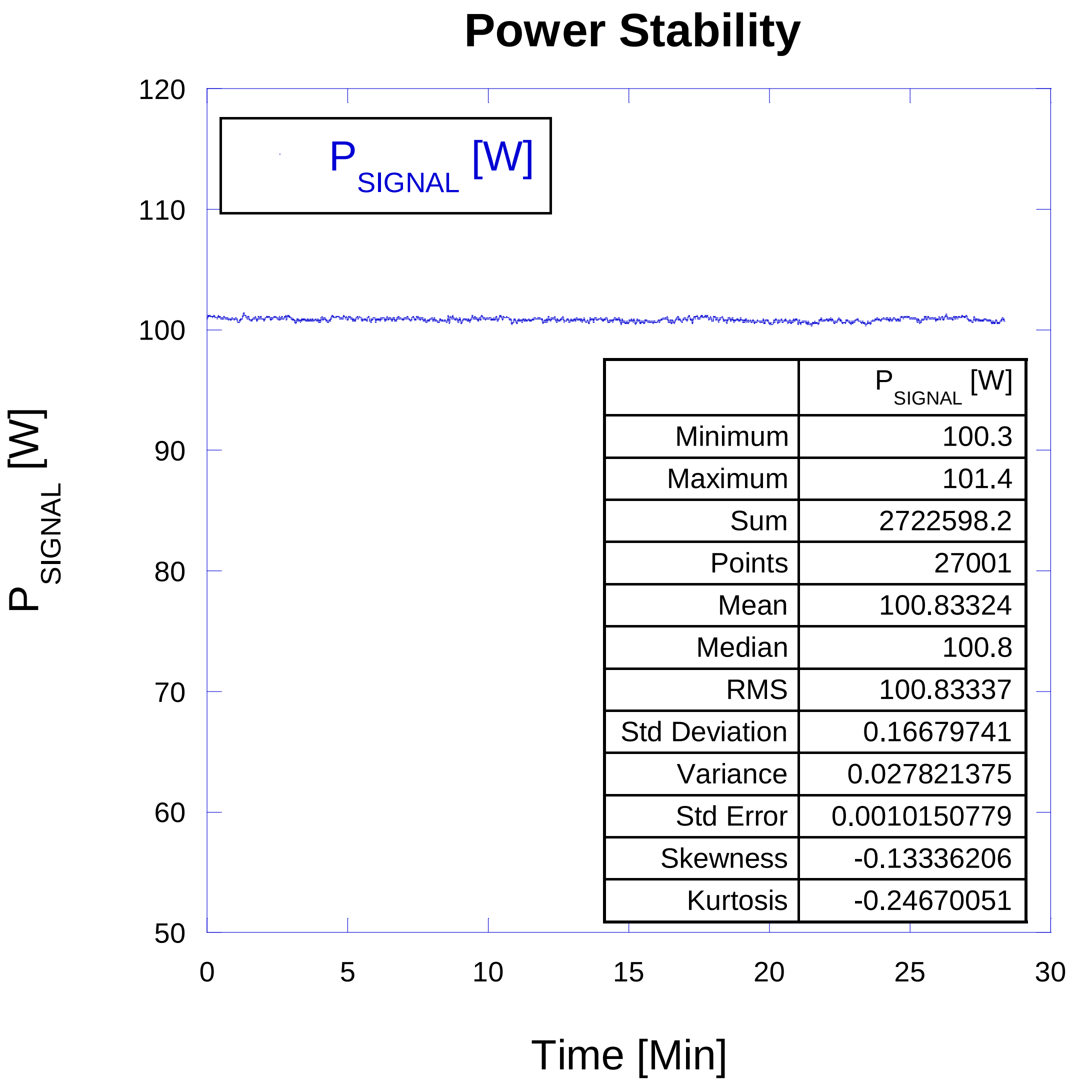
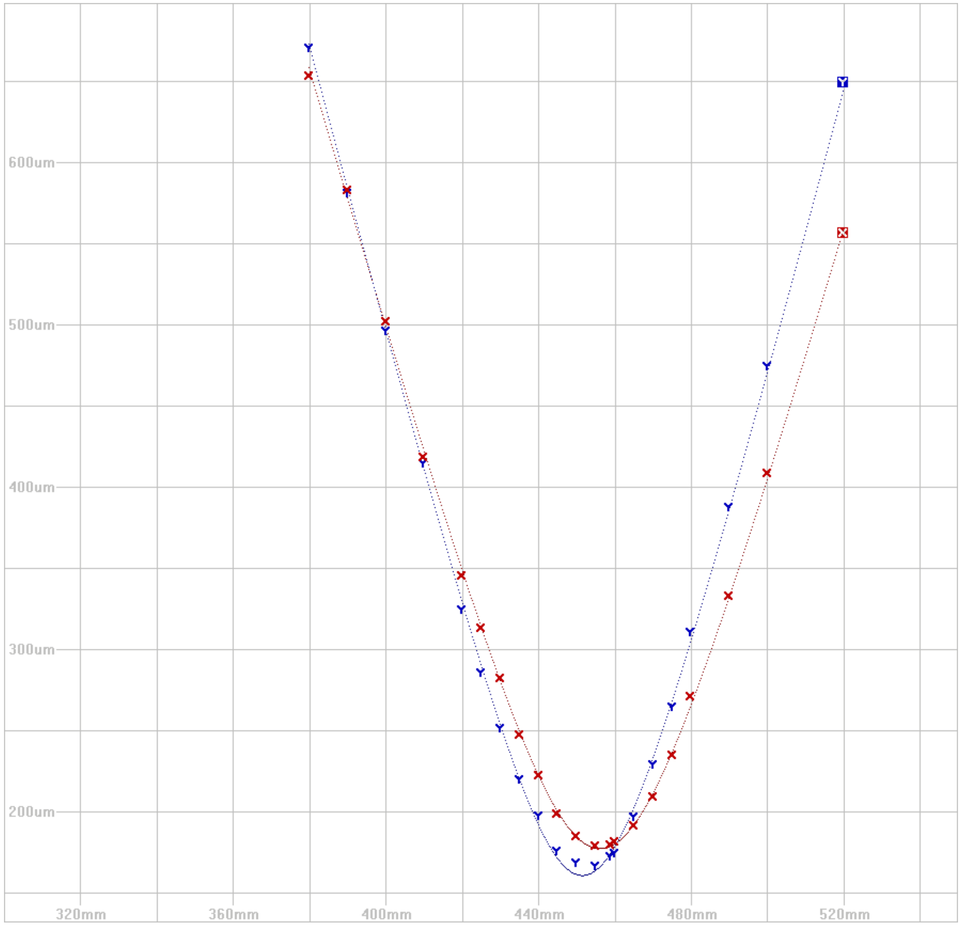
Single Frequency PM Amplifier Platform (100W at 1mm)



	P_{SIGNAL} [W]
Minimum	100.3
Maximum	101.4
Sum	2722598.2
Points	27001
Mean	100.83324
Median	100.8
RMS	100.83337
Std Deviation	0.16679741
Variance	0.027821375
Std Error	0.0010150779
Skewness	-0.13336206
Kurtosis	-0.24670051

Data collected at 100W > 4 Hours

Single Frequency PM Amplifier Platform (100W at 1mm)

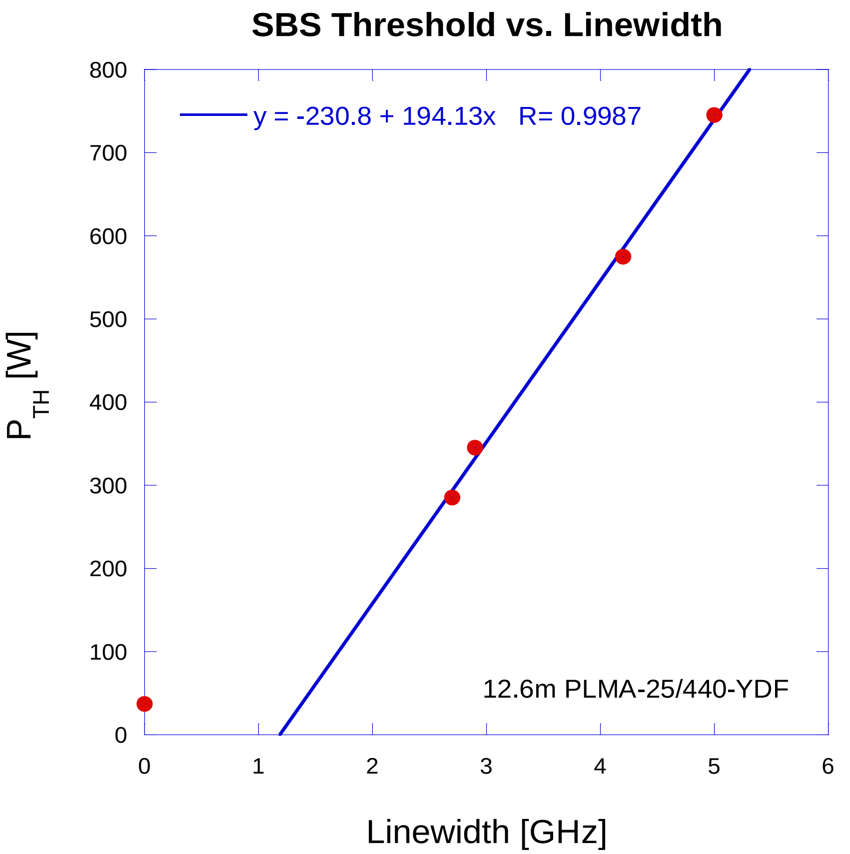


Beam Propagation Factor
100W

$M_x^2 = 1.08$

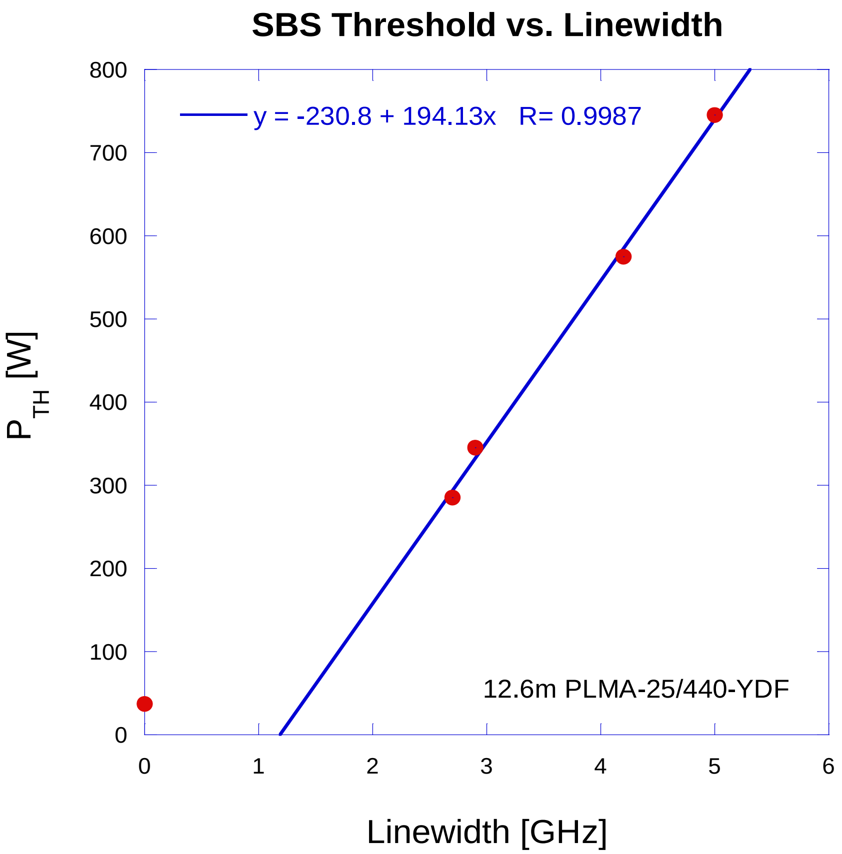
$M_Y^2 = 1.09$

SBS Threshold Depends on Linewidth of Seed Source



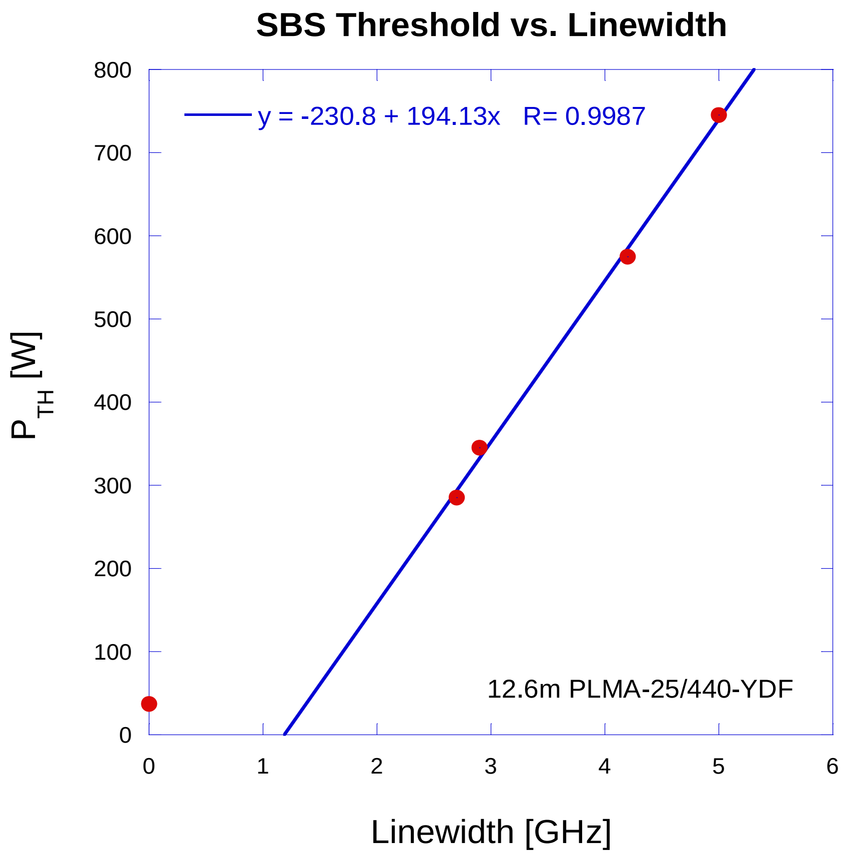
In some applications 1-10GHz linewidth is suitable (this signal linewidth reduces the SBS gain in the amplifier, which has linewidth ~50MHz)

SBS Threshold Depends on Linewidth of Seed Source



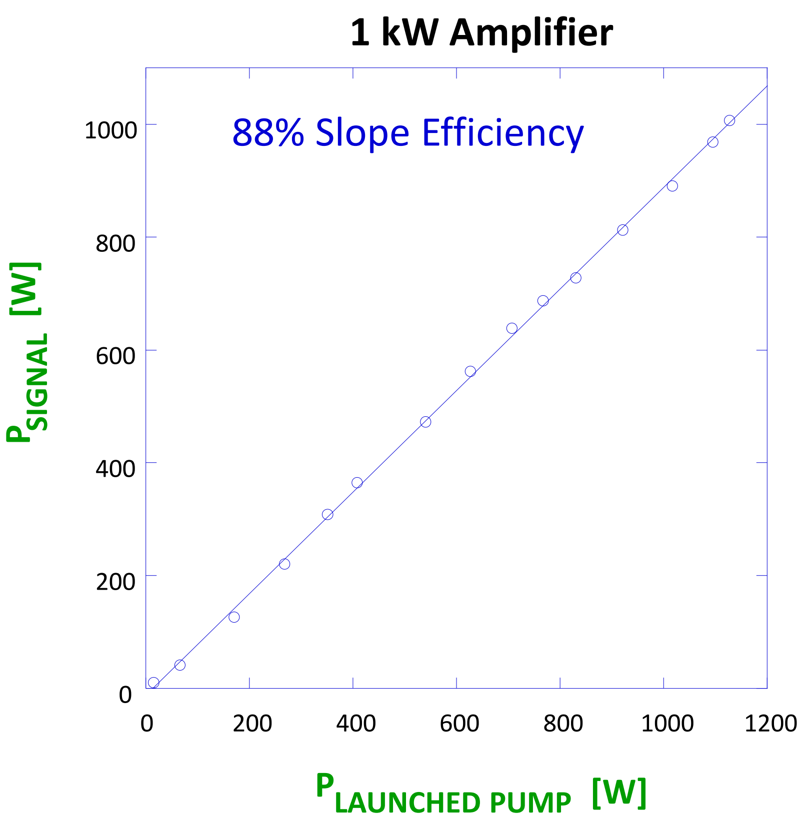
In those cases broadening the linewidth to achieve more output power is an acceptable compromise

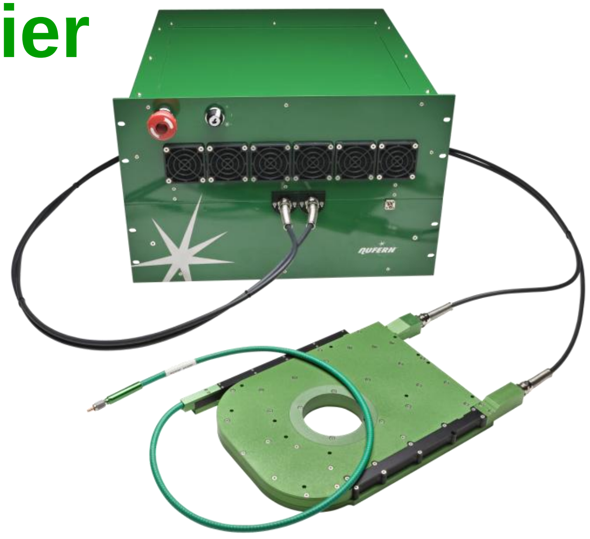
SBS Threshold Depends on Linewidth of Seed Source

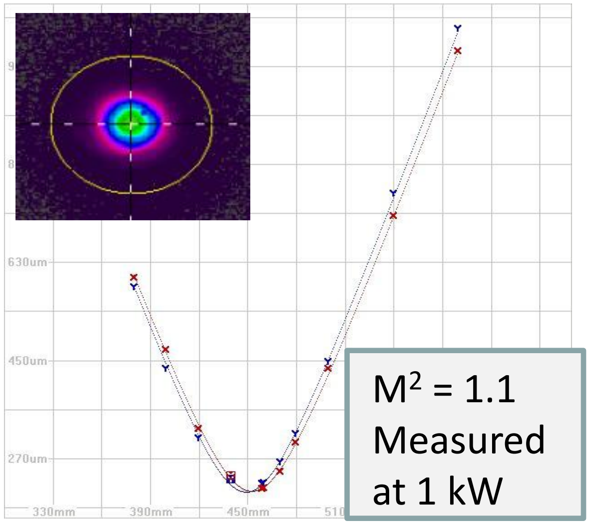


In this case LMA fibers generate output power >1kW CW

Nufern Turn-key, 1kW Amplifier (3GHz seed source)

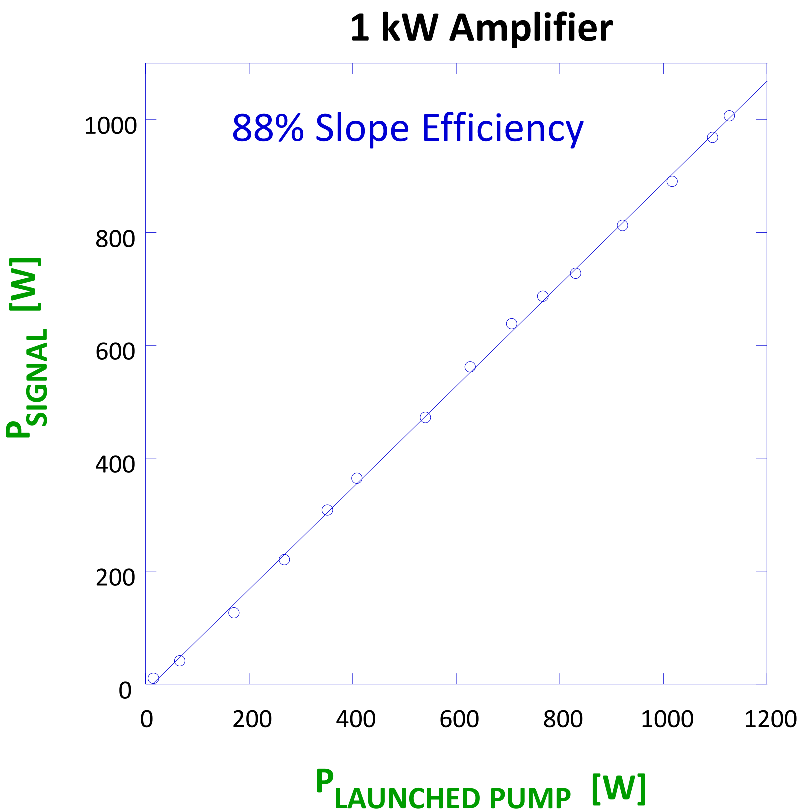


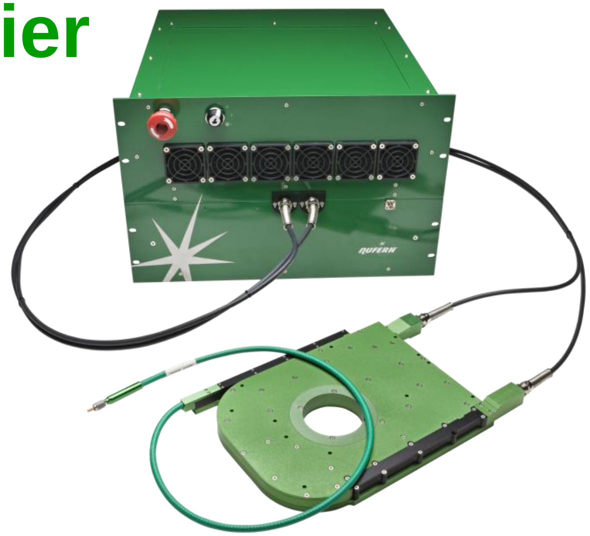


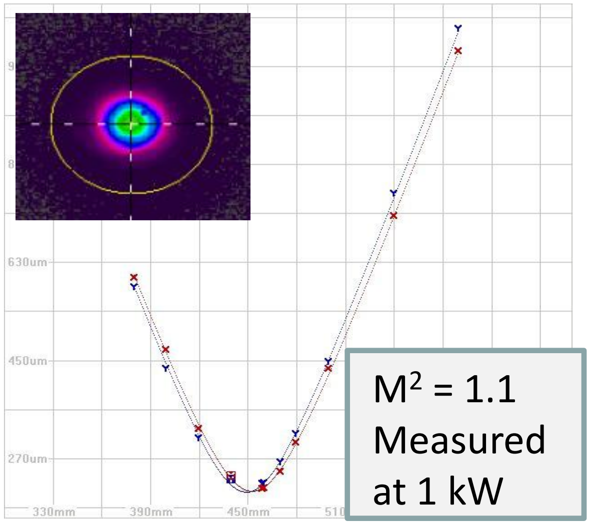


Multi-stage turn-key packed amplifier (1mW input power)

Nufern Turn-key, 1kW Amplifier (3GHz seed source)

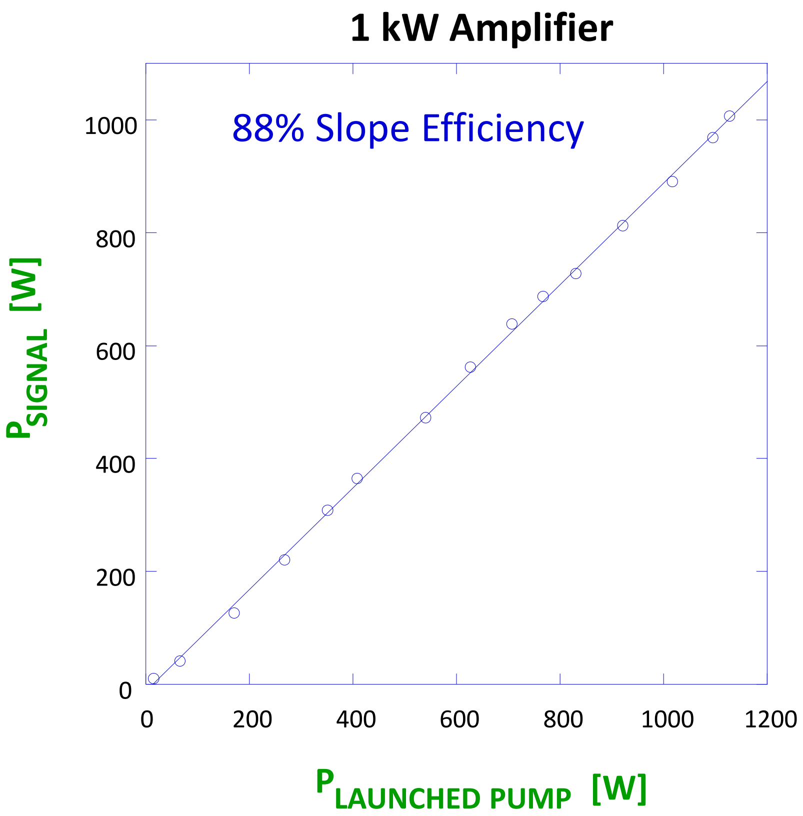


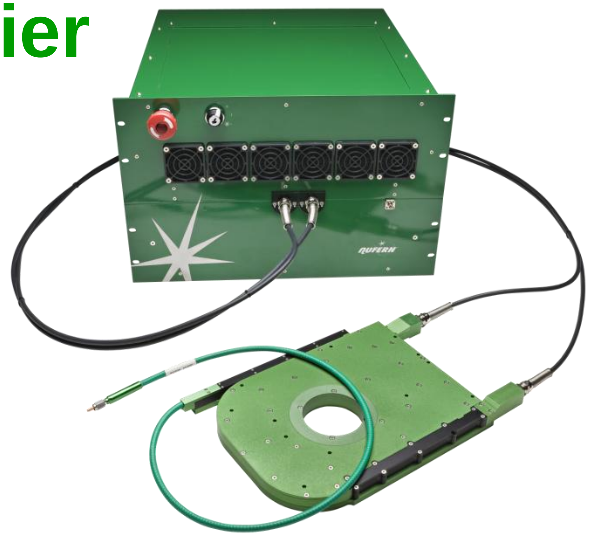


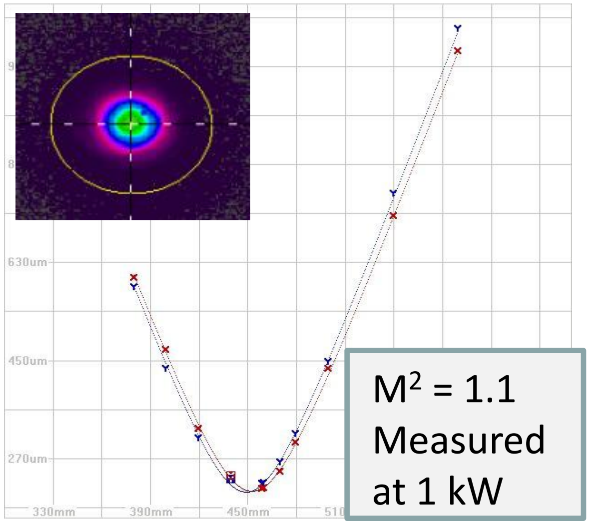


Signal Linewidth 3~10GHz

Nufern Turn-key, 1kW Amplifier (3GHz seed source)

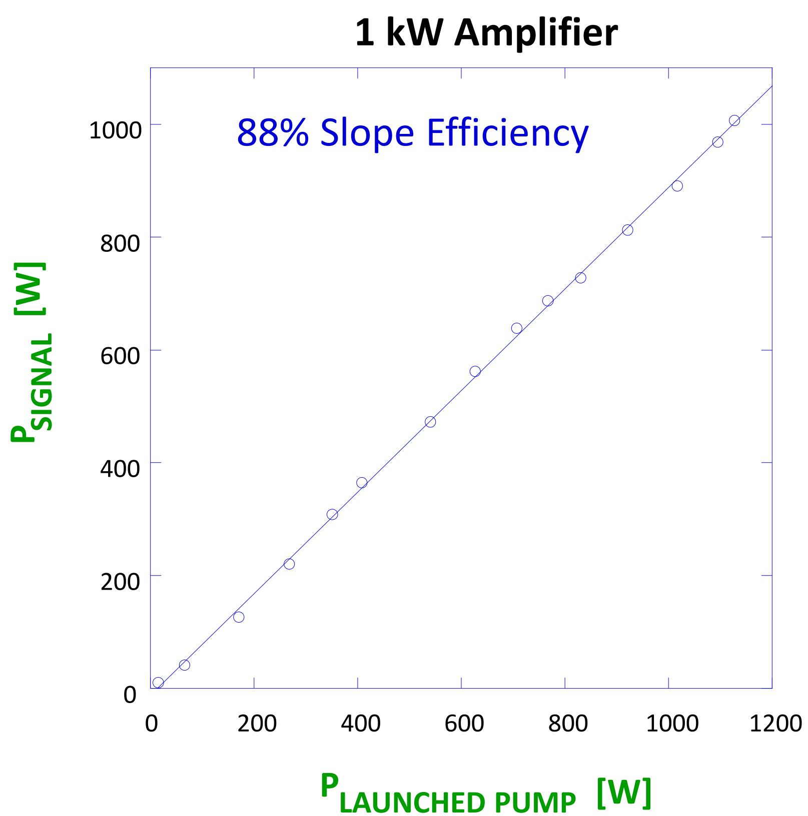


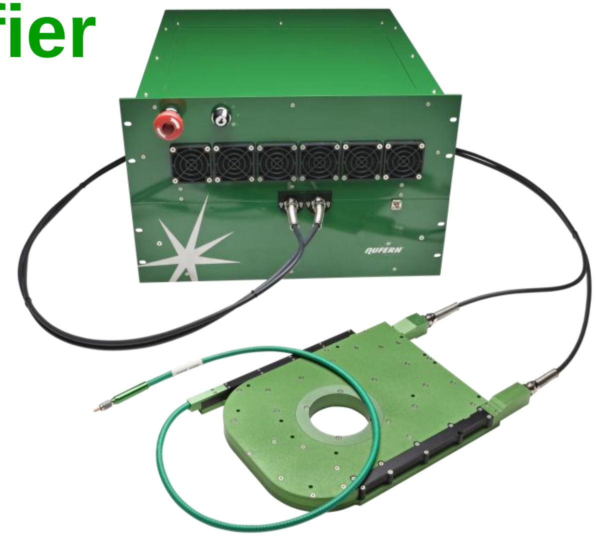


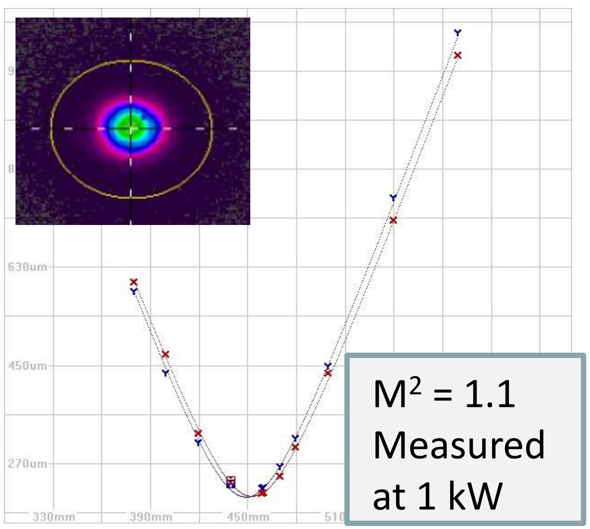


Linearly polarized option PER~13dB

Nufern Turn-key, 1kW Amplifier (3GHz seed source)

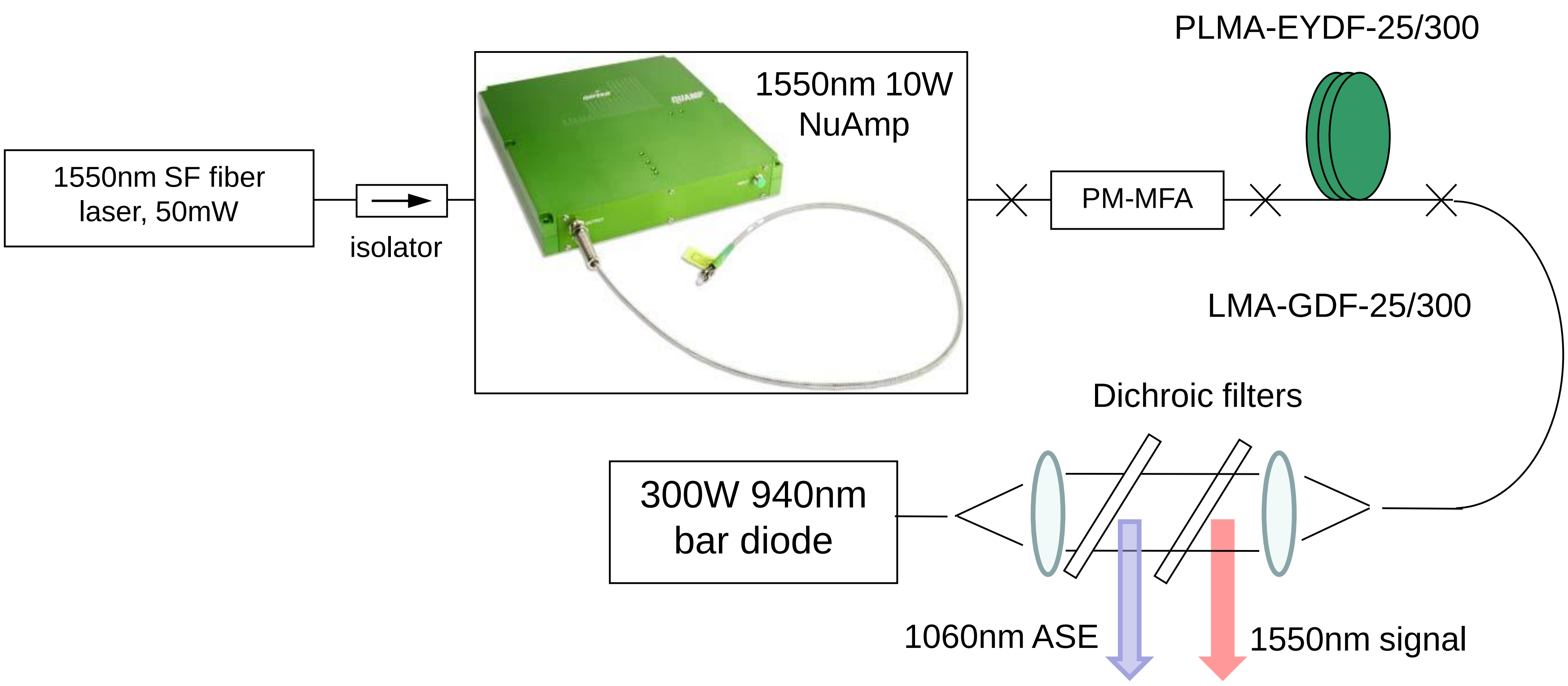






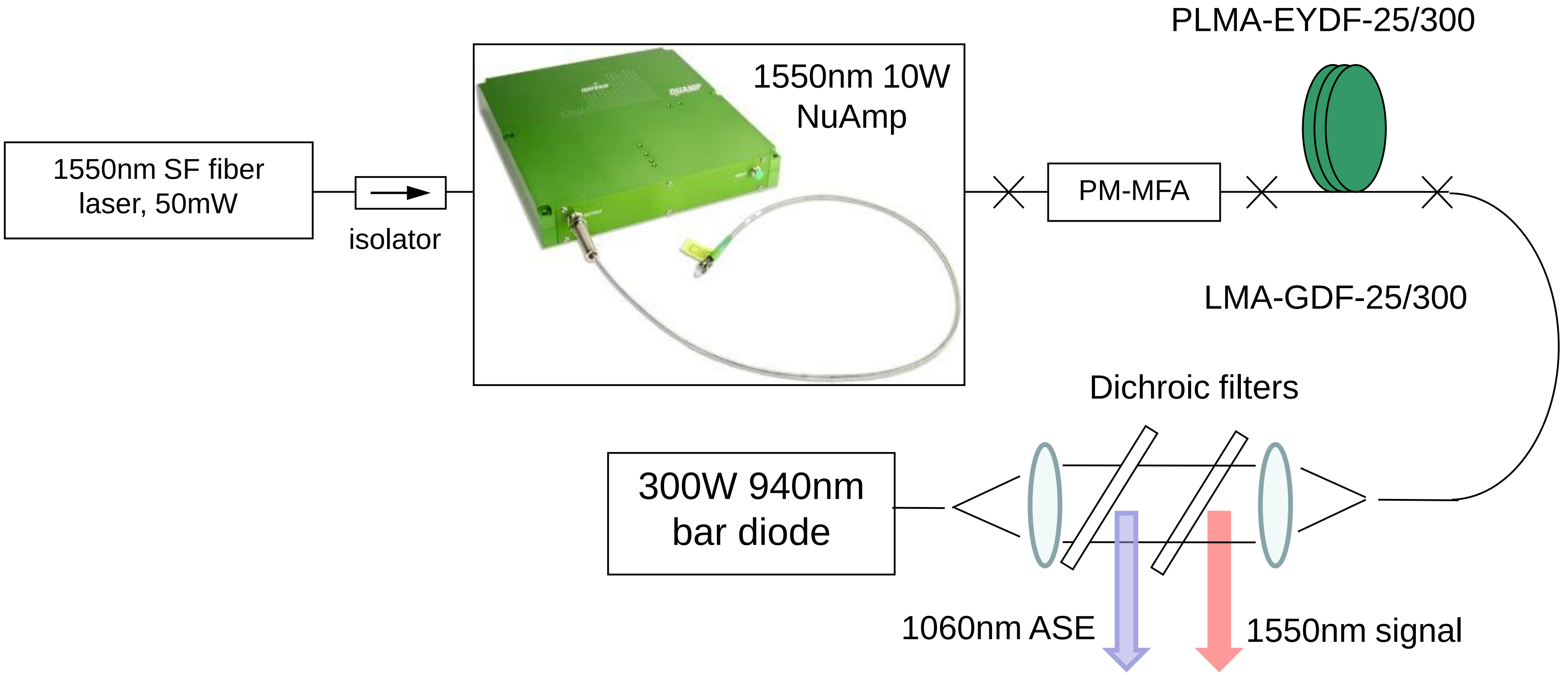
Multiple units shipped 2008-2009

High Power Single Frequency 1.5μm PM-LMA Amp



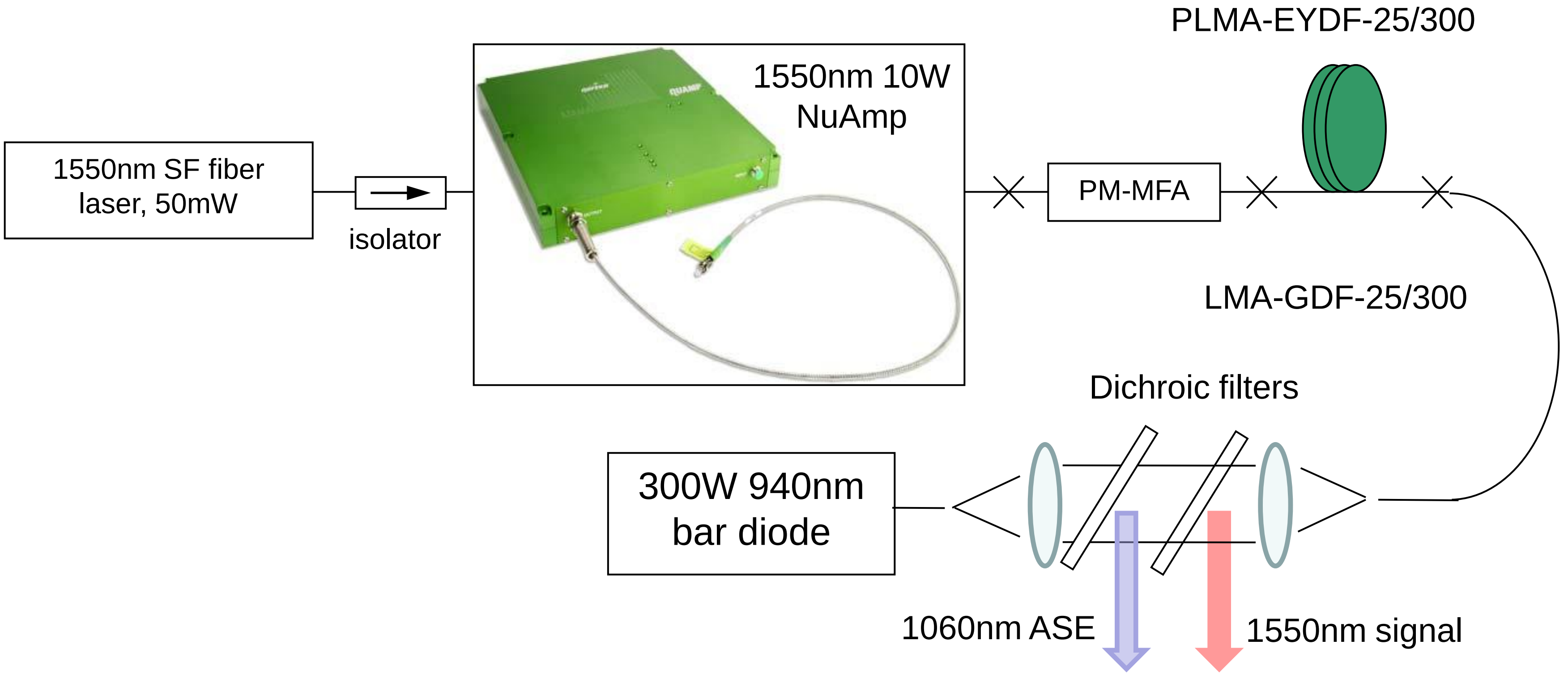
50mW 1550nm single-frequency seed fiber laser, 5kHz linewidth

High Power Single Frequency 1.5μm PM-LMA Amp



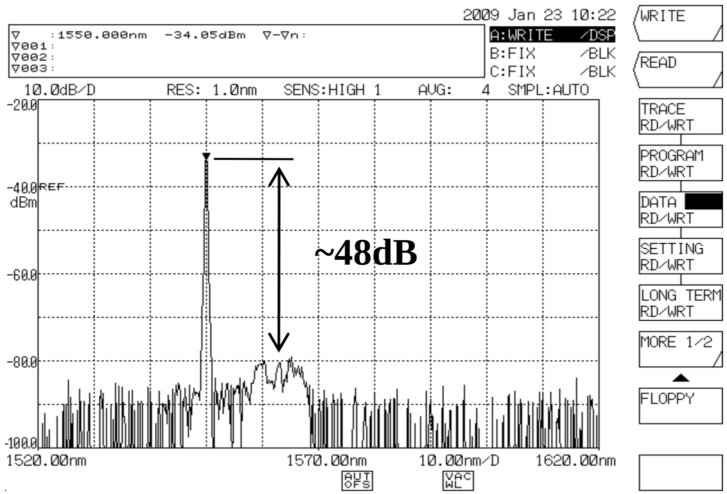
10W PM single-frequency pre-amp (NuAMP)

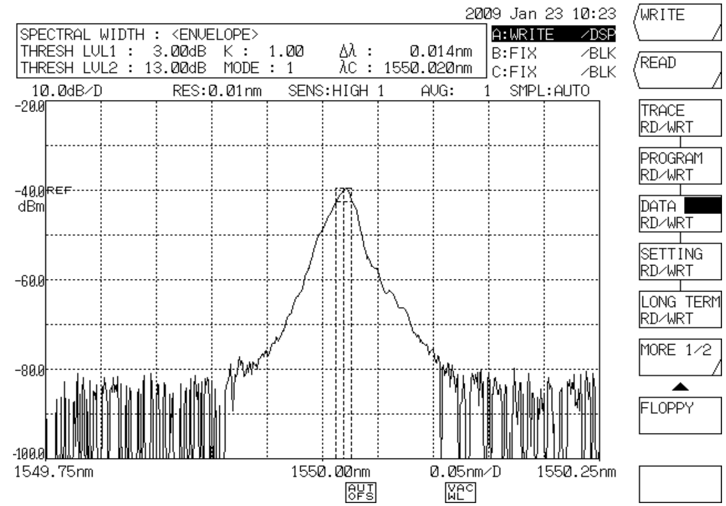
High Power Single Frequency 1.5μm PM-LMA Amp



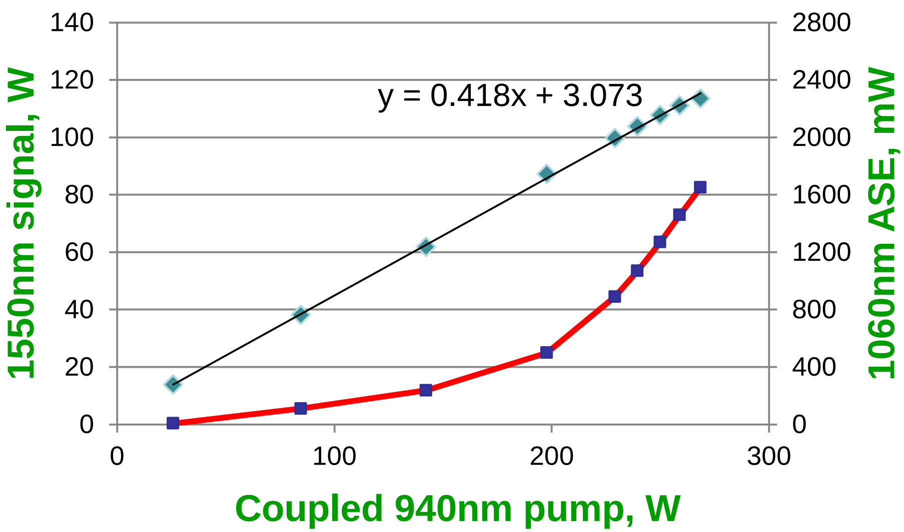
Amplified in Er:Yb PM LMA 25/300 fiber, counter pumped at 940nm

High Power Single Frequency 1.5µm PM-LMA Amp



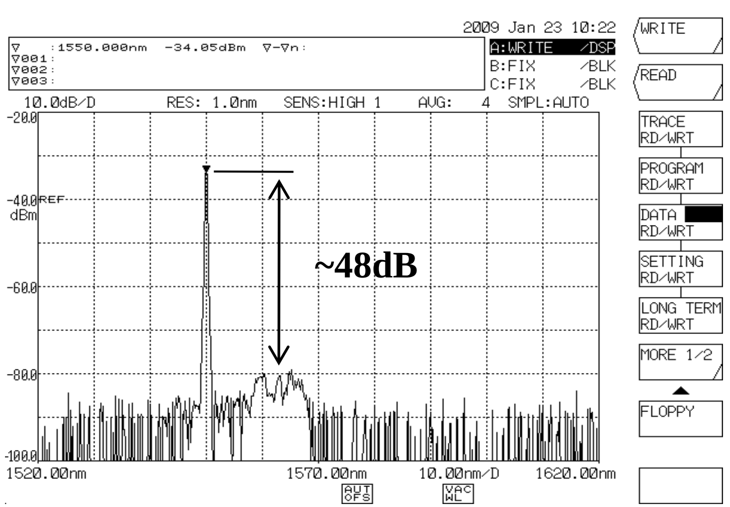


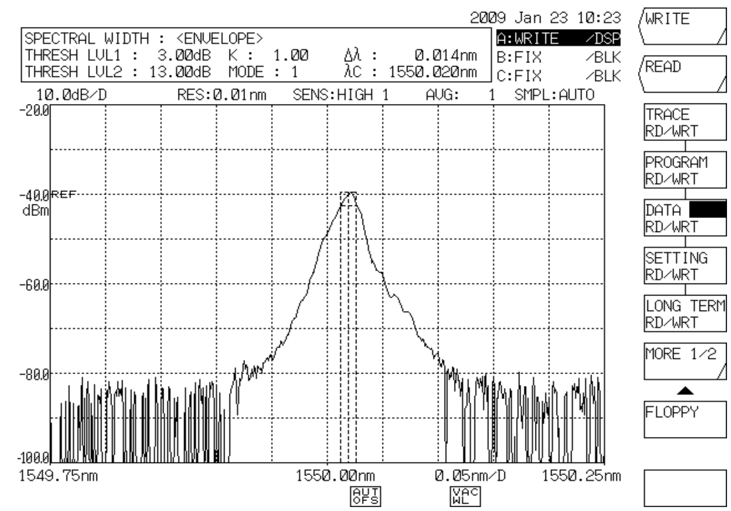
PM SF 1550nm amp efficiency test EYDF-25/300



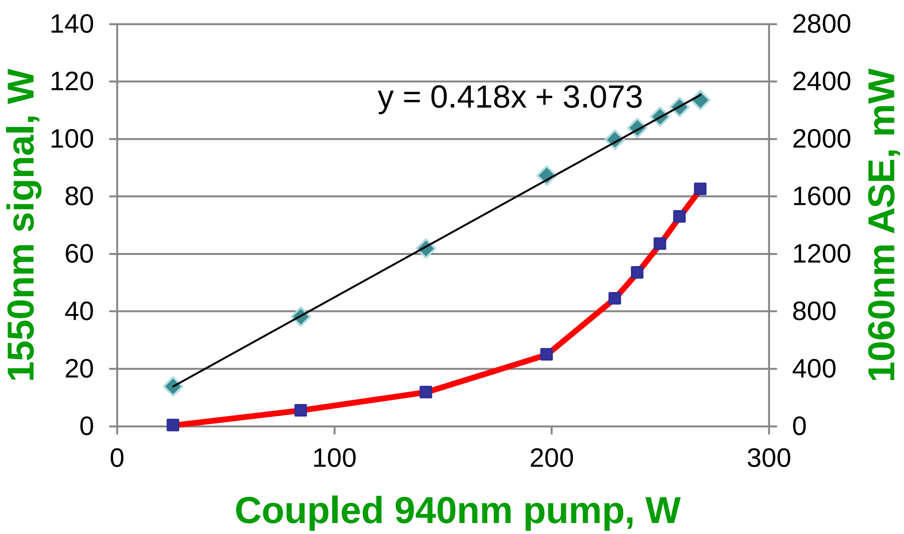
1550nm 5kHz input signal linewidth

High Power Single Frequency 1.5μm PM-LMA Amp



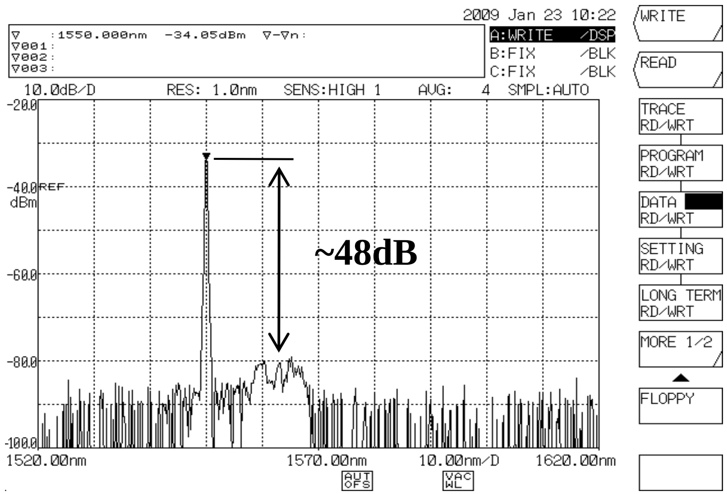


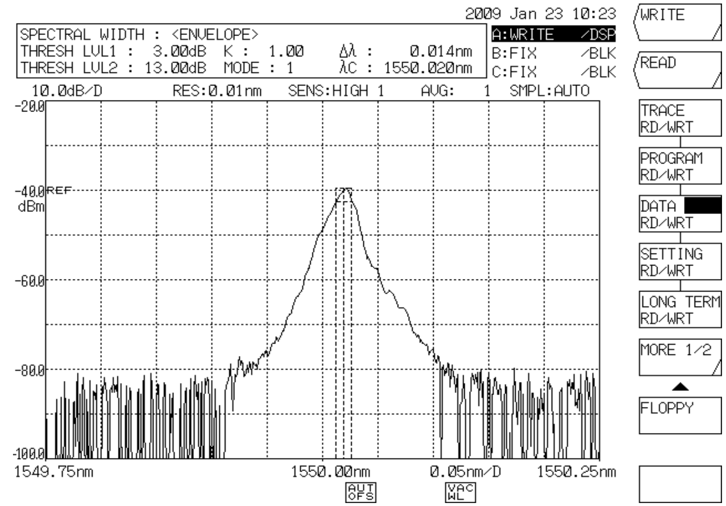
PM SF 1550nm amp efficiency test EYDF-25/300



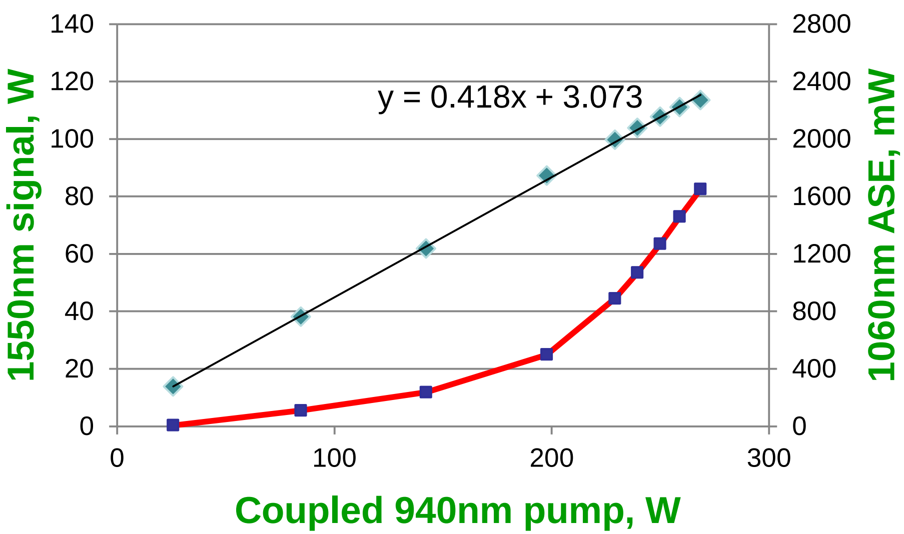
113W output

High Power Single Frequency 1.5μm PM-LMA Amp



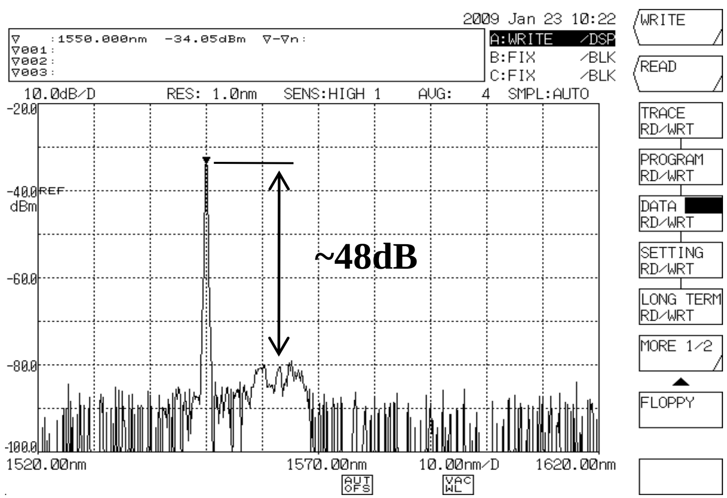


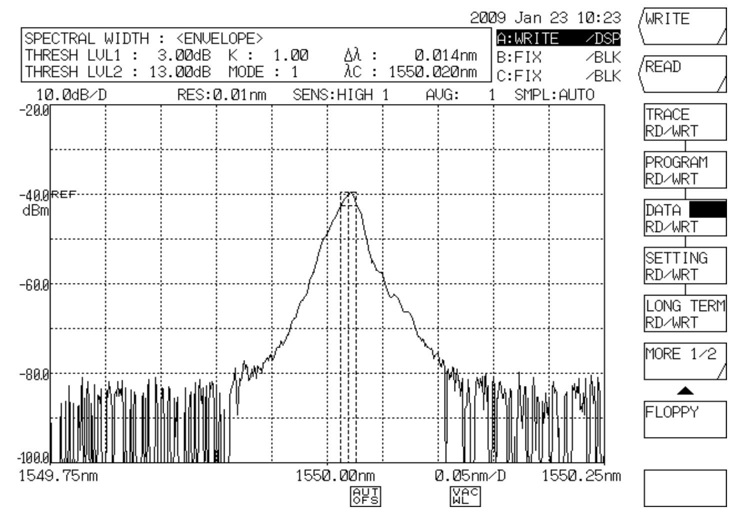
PM SF 1550nm amp efficiency test EYDF-25/300



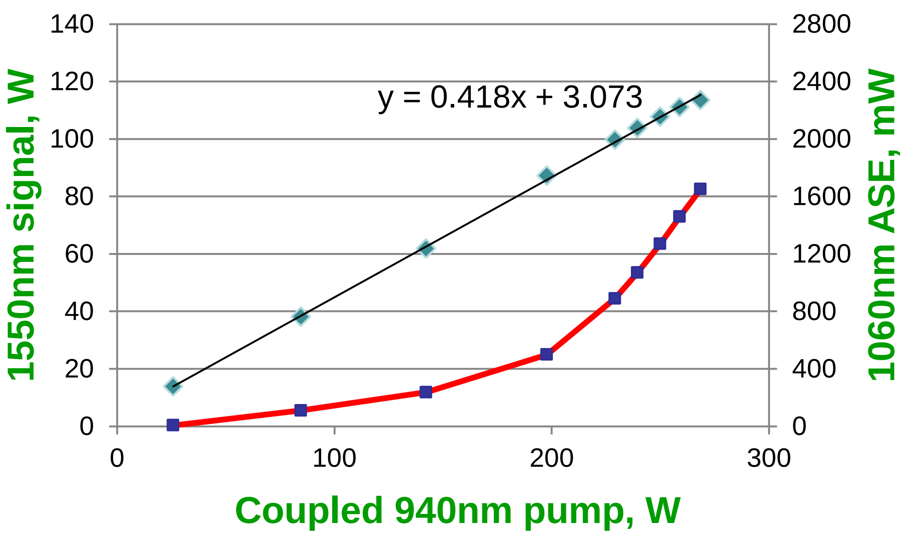
41.8% slope efficiency

High Power Single Frequency 1.5μm PM-LMA Amp



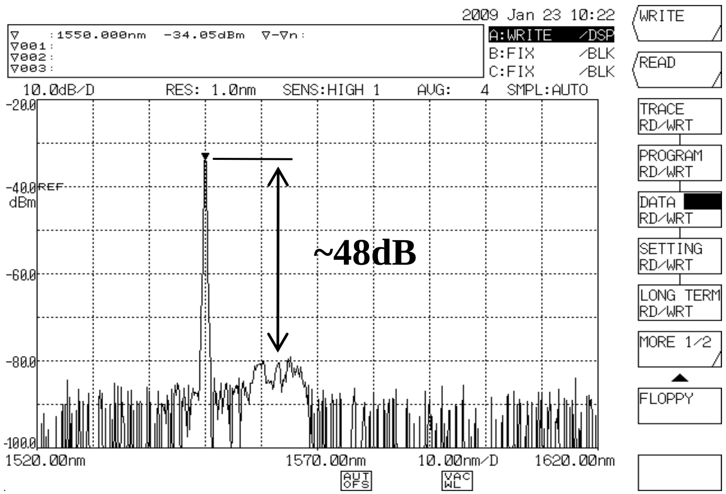


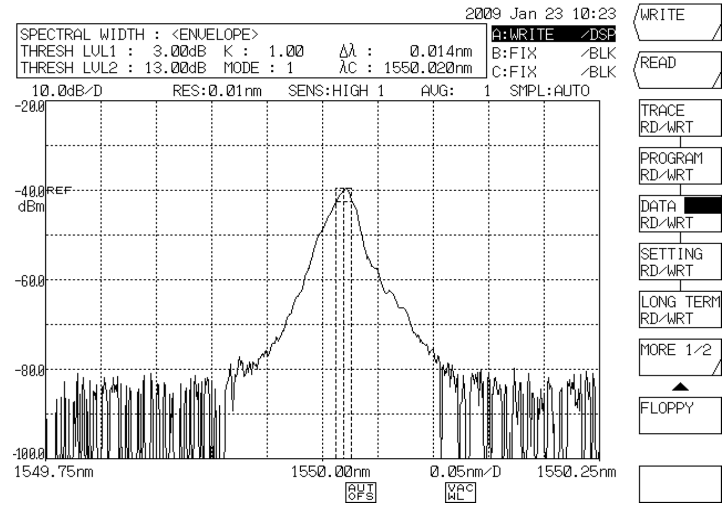
PM SF 1550nm amp efficiency test EYDF-25/300



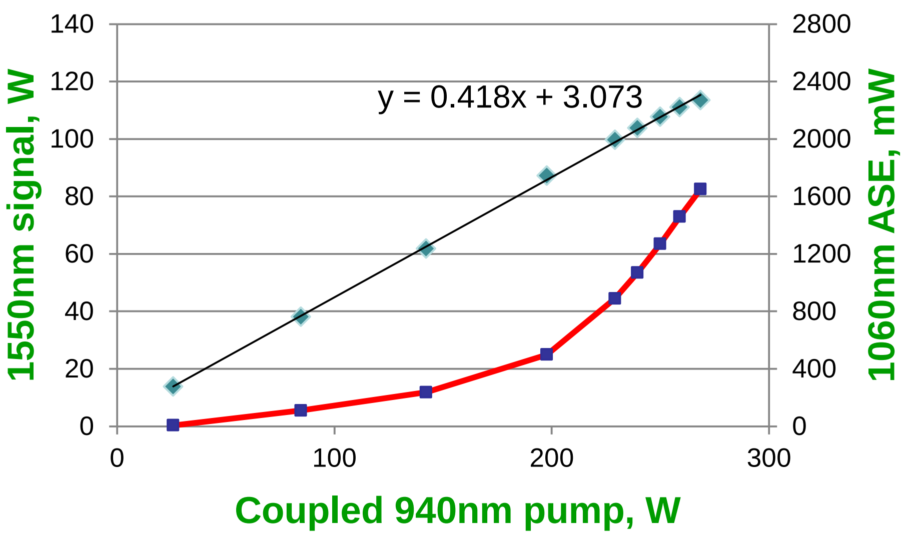
PER 13dB

High Power Single Frequency 1.5μm PM-LMA Amp



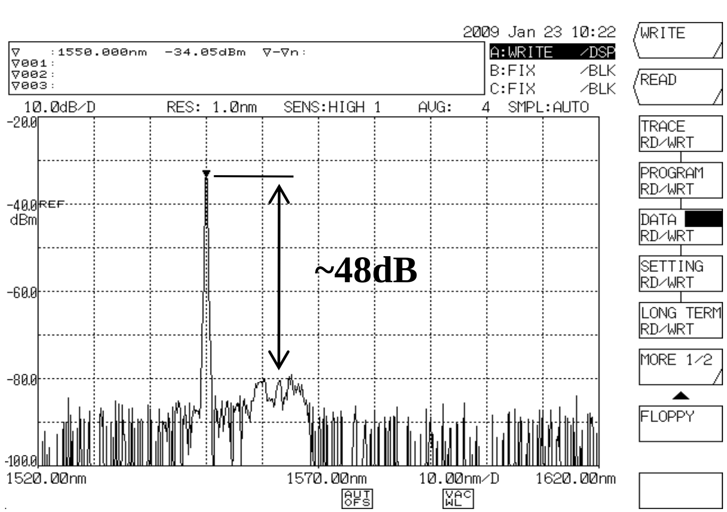


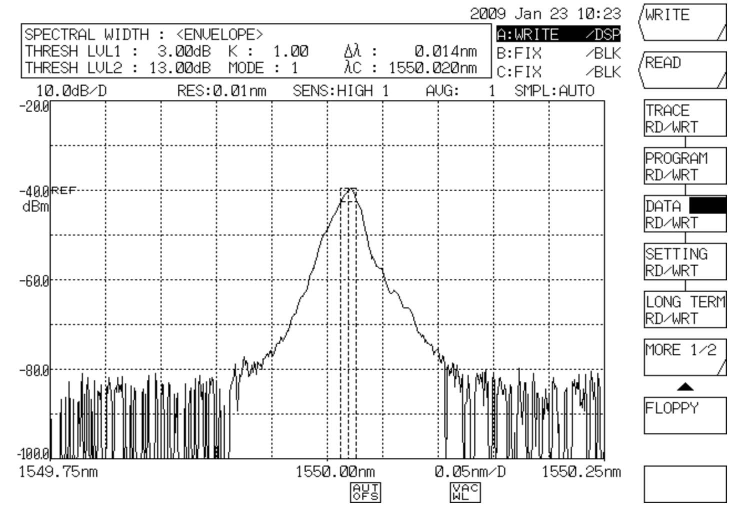
PM SF 1550nm amp efficiency test EYDF-25/300



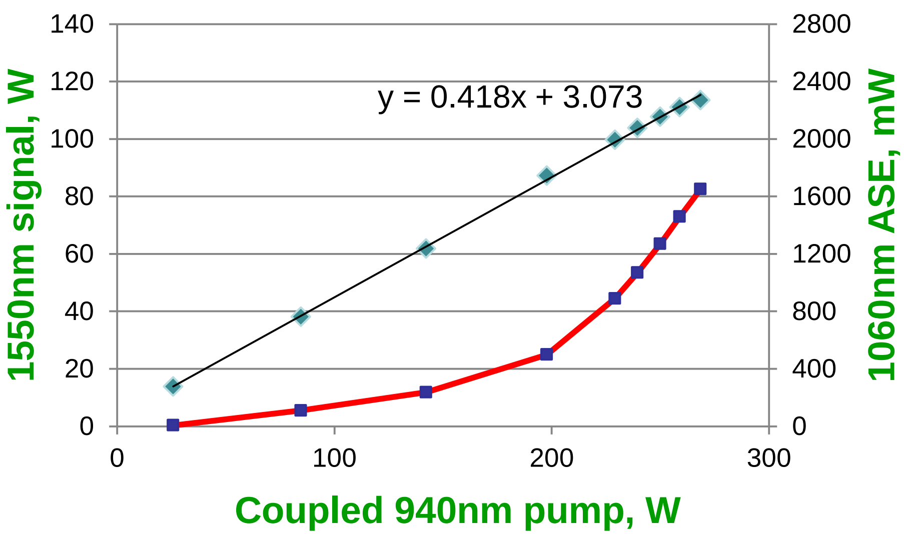
~48dB 1550nm ASE suppression

High Power Single Frequency
1.5μm PM-LMA Amp





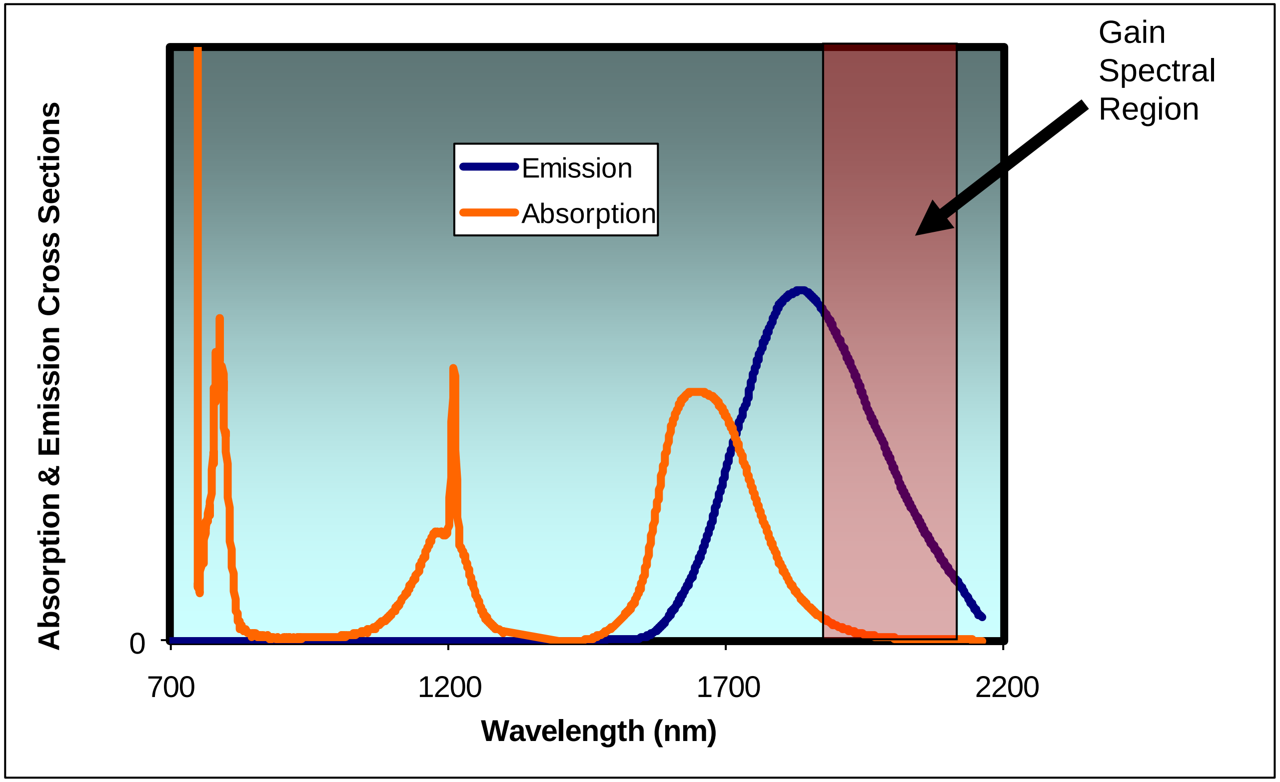
PM SF 1550nm amp efficiency test EYDF-25/300



<2W 1060nm ASE

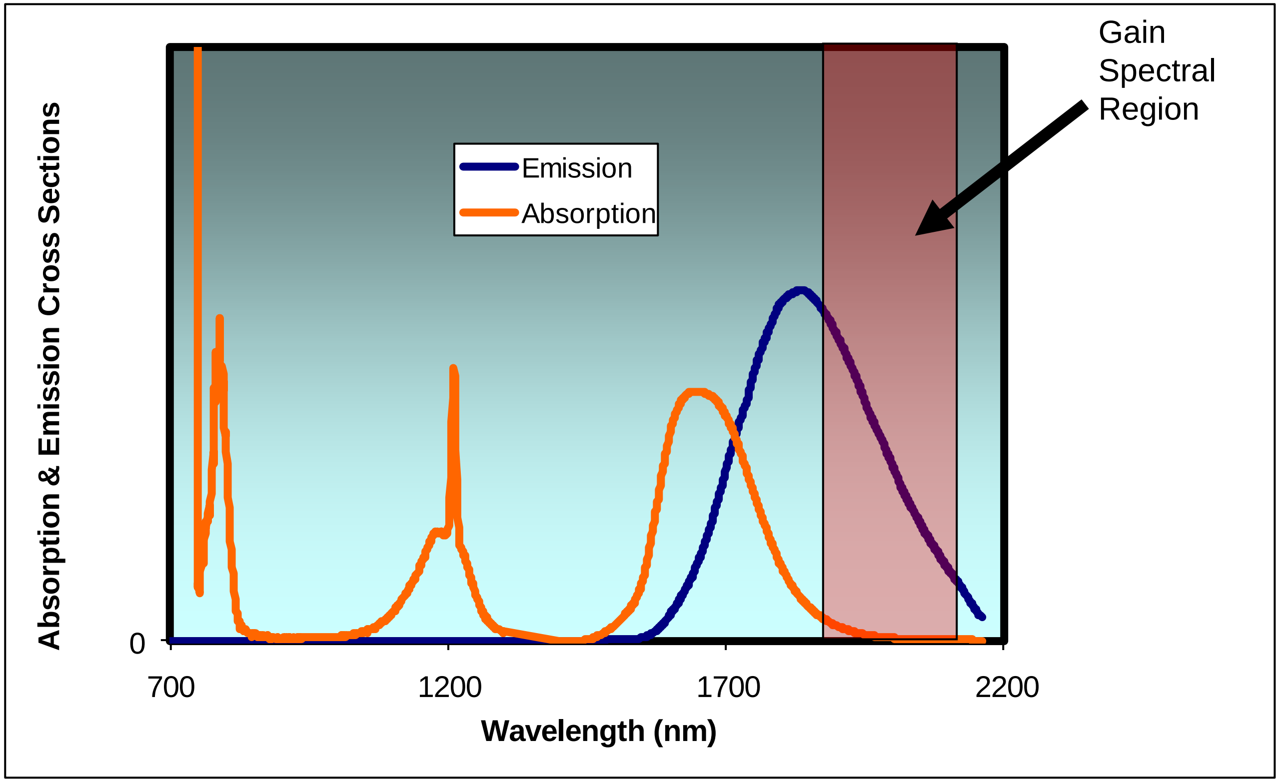
Recent Advances in Tm-fibers for 2μm Wavelength

Pump Options for Tm-doped Fibers



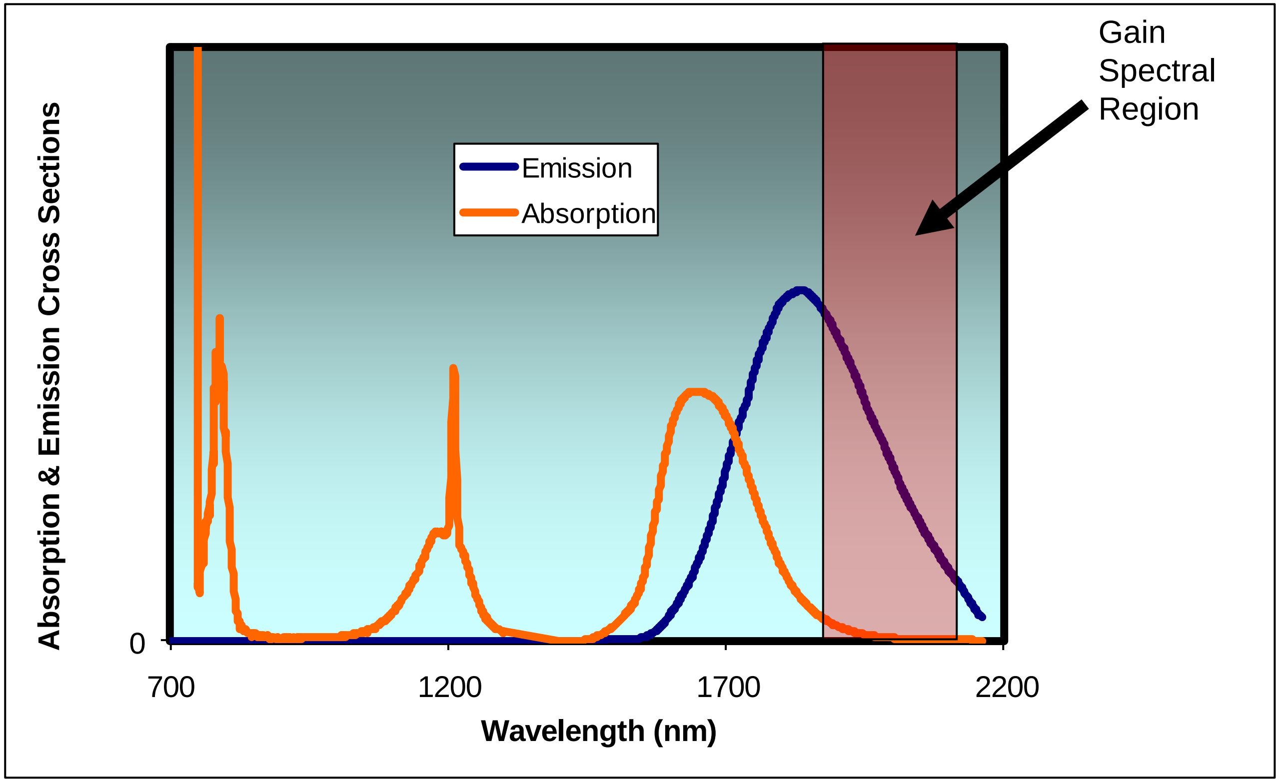
Resonant pumping around 1560nm is difficult to power scale with direct diode pumping (no high power/brightness pumps)

Pump Options for Tm-doped Fibers



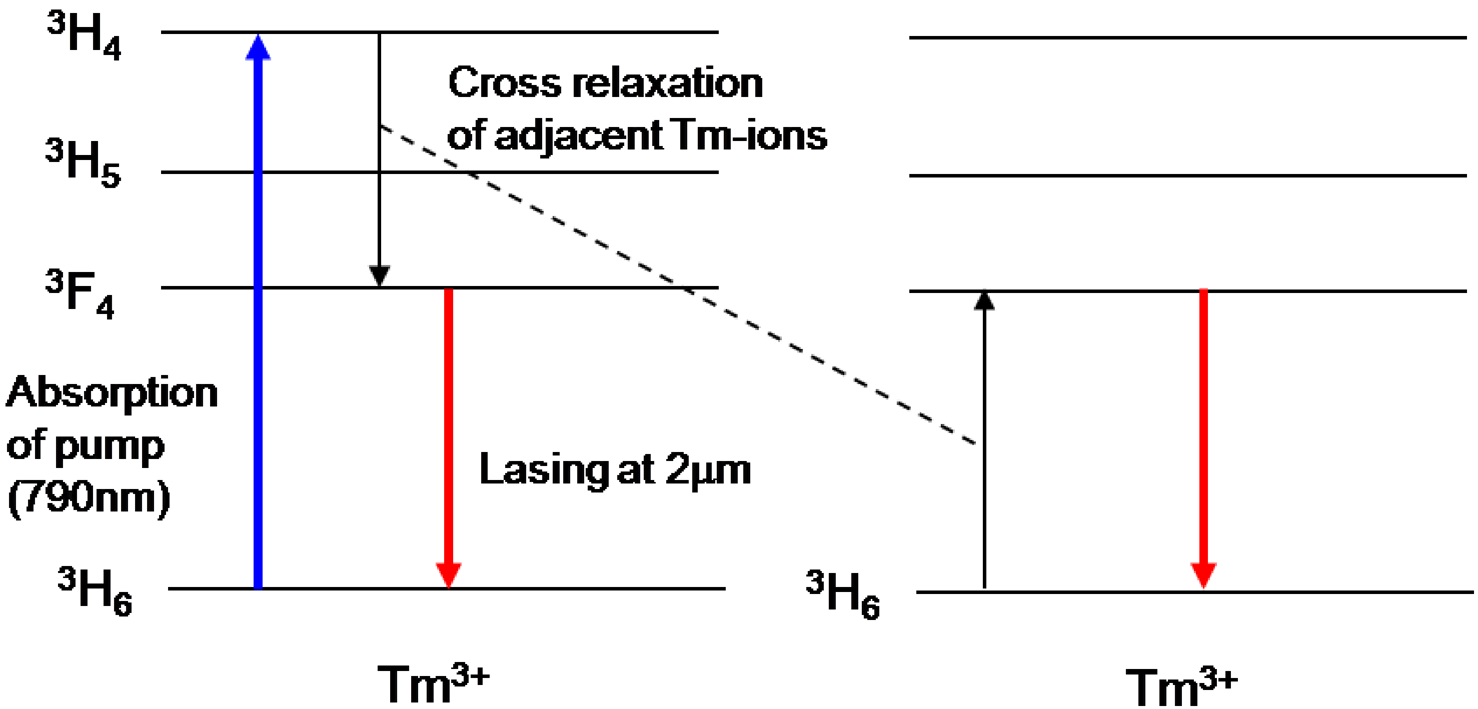
Solution here is to pump with Er:Yb fiber laser which is in turn pumped by 9xx high brightness diodes (>400W output power demonstrated, IPG 2007)

Pump Options for Tm-doped Fibers



However, the overall E-O the efficiency is low using this scheme

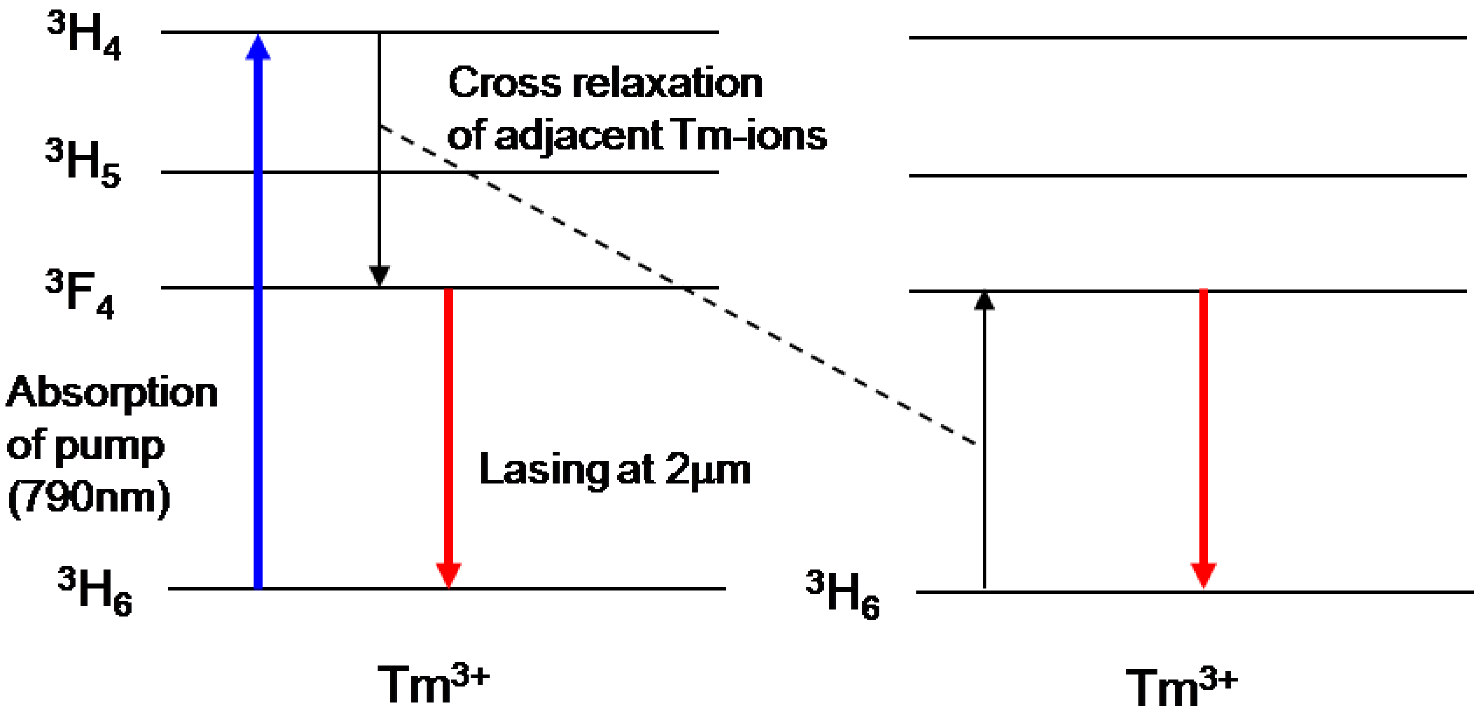
Historical Perspective on 790nm pumped Tm-fibers



Increasing the Tm^{3+} concentration decreases the ion-ion separation to enhance the 2 for 1 cross-relaxation process.

Pumping at 790nm is attractive because of the compatibility with 808nm pump diode; however, the quantum efficiency needs to be improved to be practical

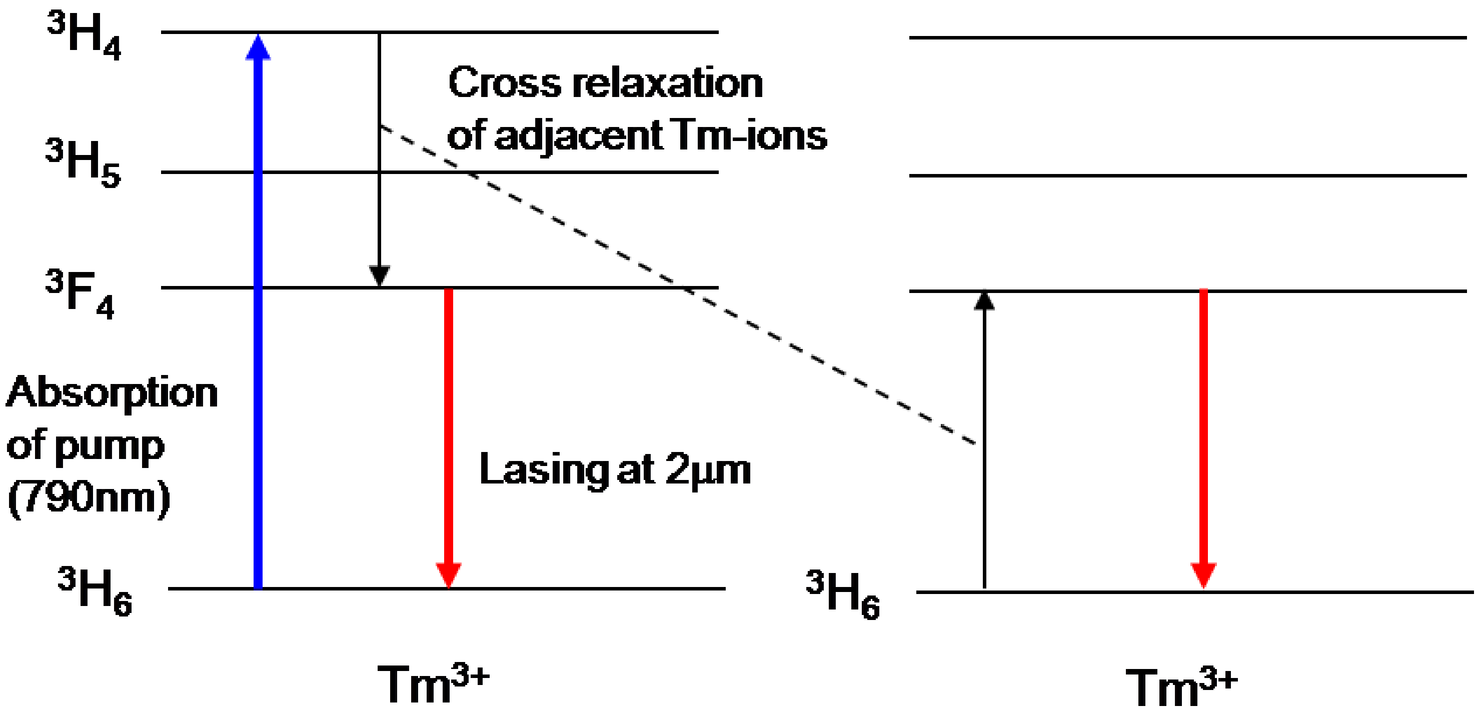
Historical Perspective on 790nm pumped Tm-fibers



Increasing the Tm^{3+} concentration decreases the ion-ion separation to enhance the 2 for 1 cross-relaxation process.

Early work on power scaling efficient Tm-doped silica fibers attributed to Jackson et al. (Uni. Sydney, Aus) and Clarkson et al (ORC, Southampton, UK)

Historical Perspective on 790nm pumped Tm-fibers



Increasing the Tm^{3+} concentration decreases the ion-ion separation to enhance the 2 for 1 cross-relaxation process.

Both groups recognized early on that optimizing the cross relaxation process in highly doped silica fibers could improve the efficiency of 790nm pumped fibers

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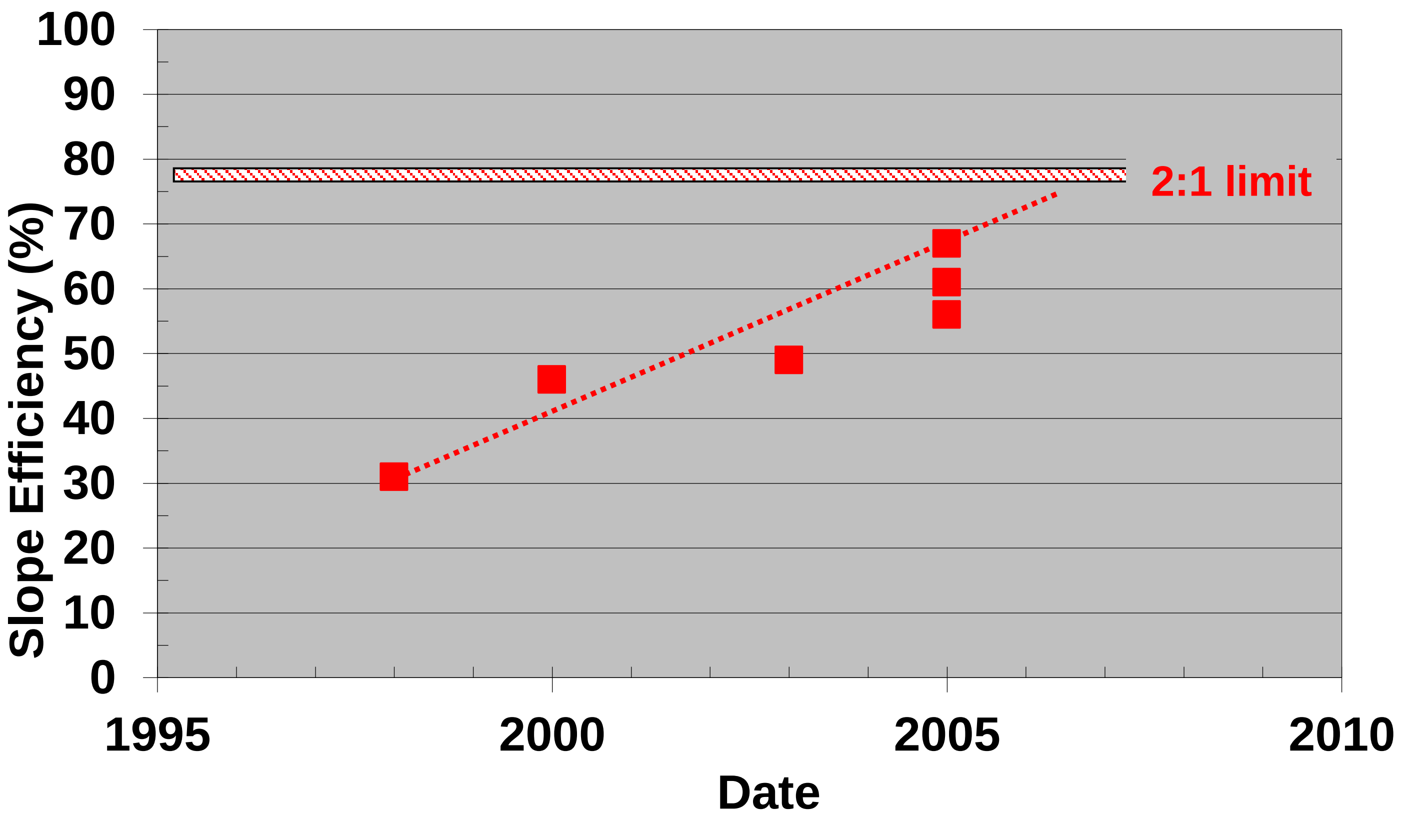
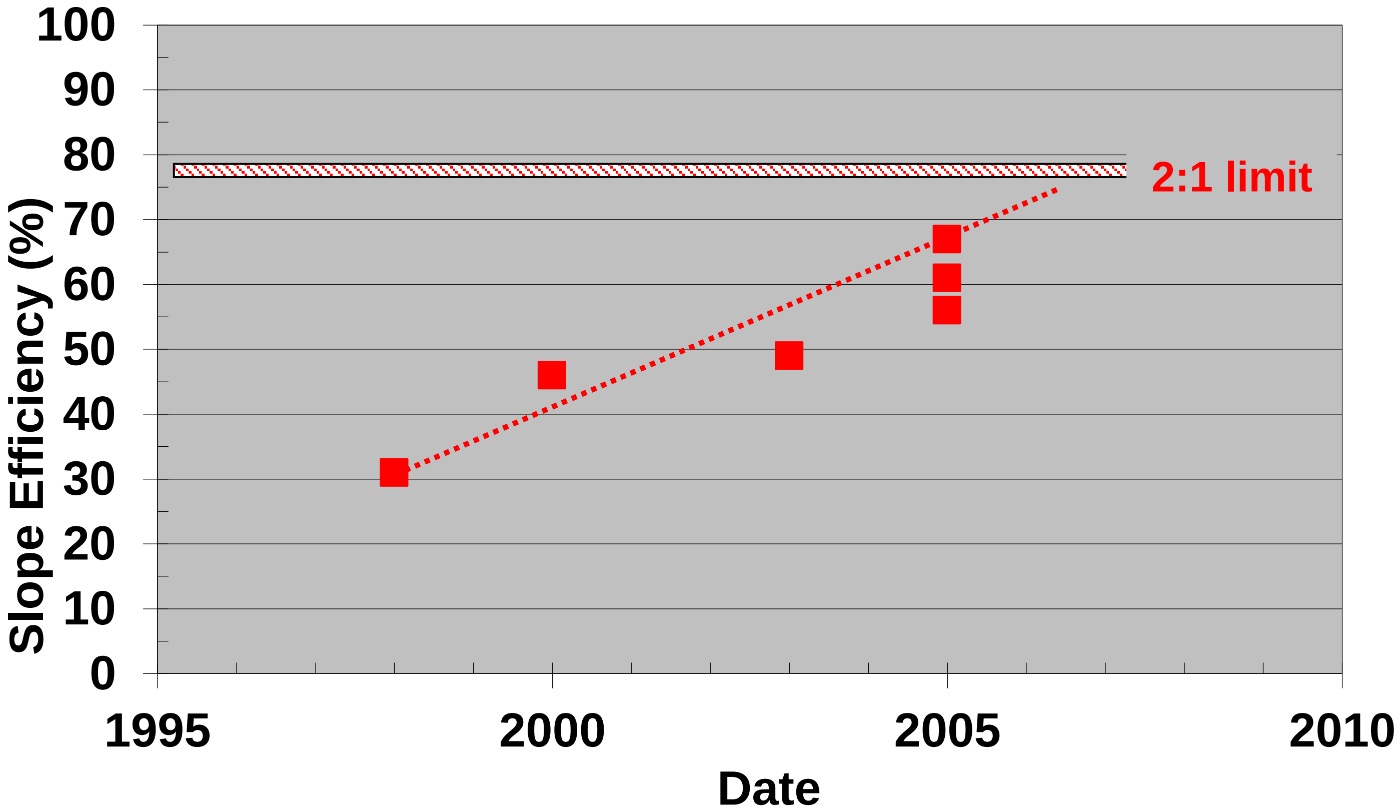
Improvements in Fiber Efficiency over the Years



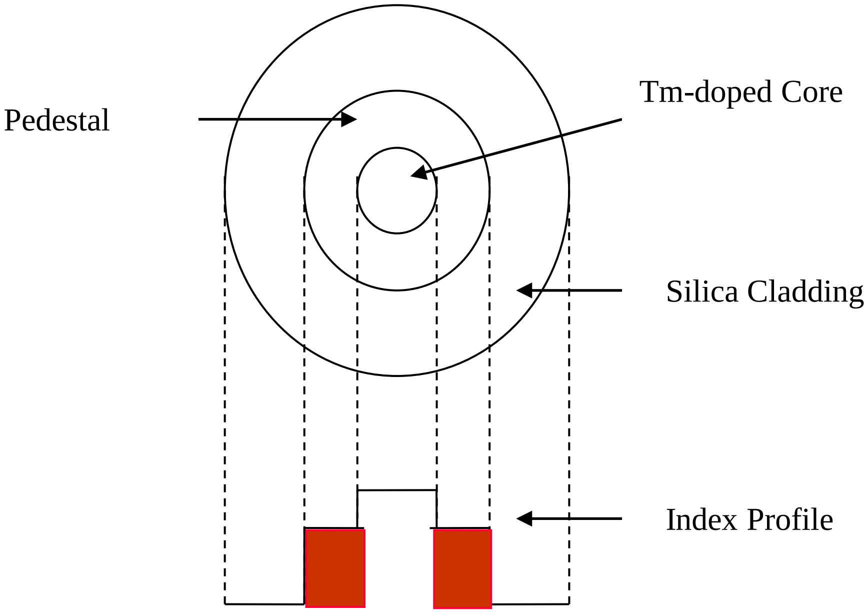
To date >65% slope efficiency has been demonstrated for 790nm pumped fibers operating around 2μm, approaching the theoretical limit

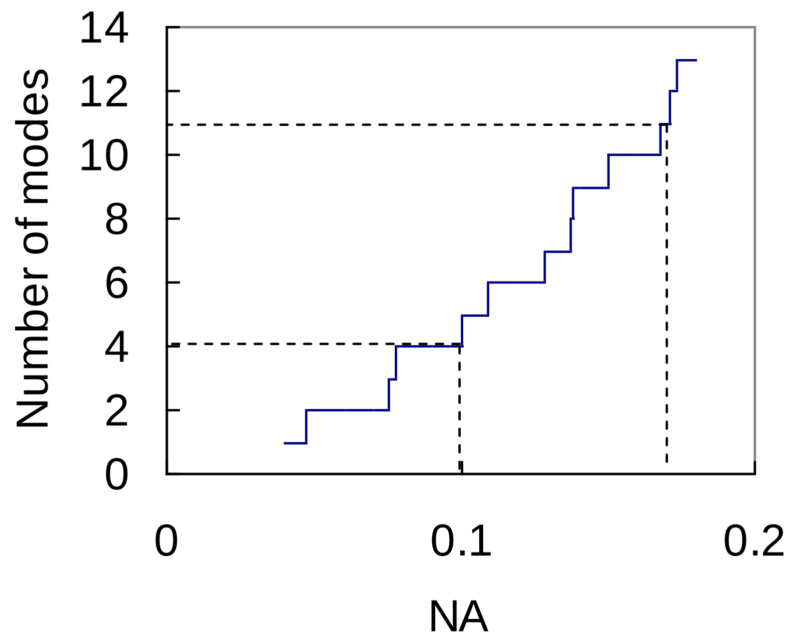
Improvements in Fiber Efficiency over the Years



Far exceeding the overall E-O efficiency of resonant pumped Tm-fiber systems

Tm-doped LMA Fibers for Single Mode Beam Quality

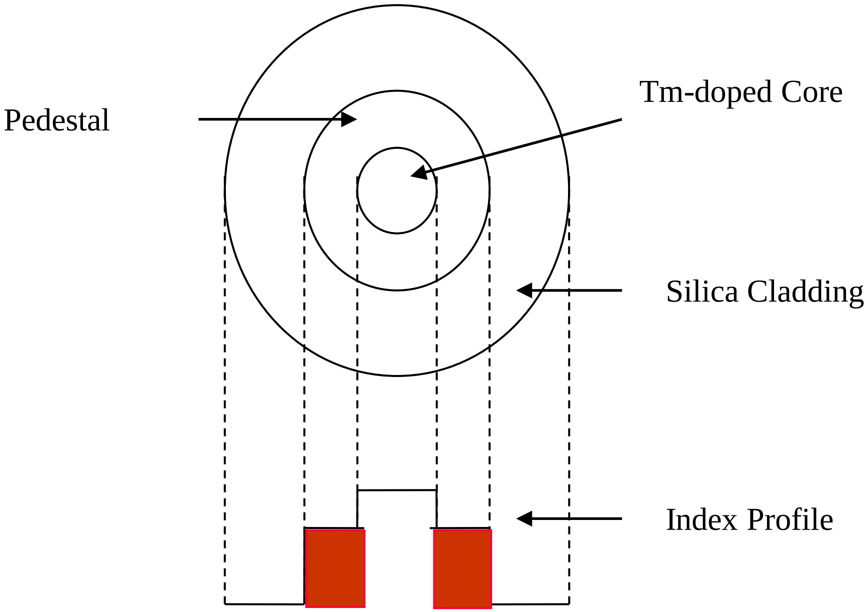


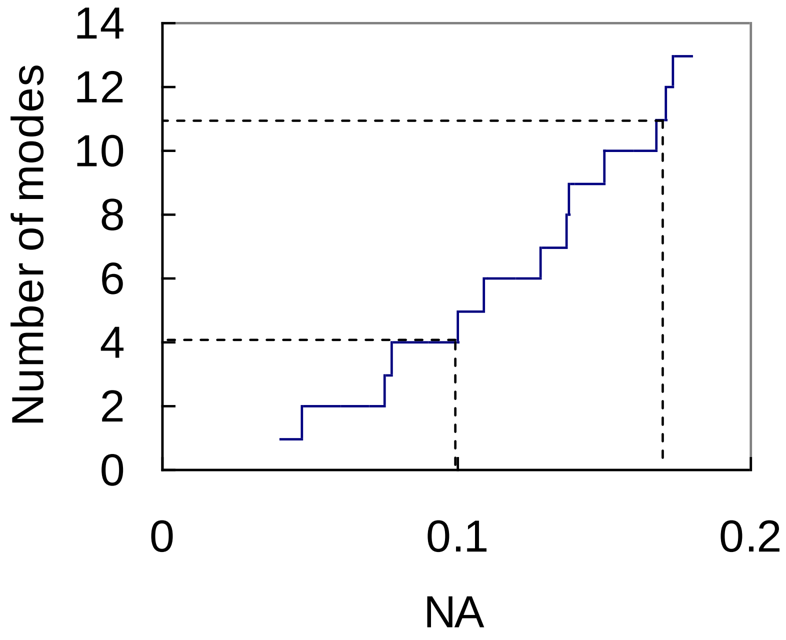


Much of the early high efficiency Tm-doped fibers were multimode because of the high NA

(A. Carter et al., CLEO 2007)

Tm-doped LMA Fibers for Single Mode Beam Quality

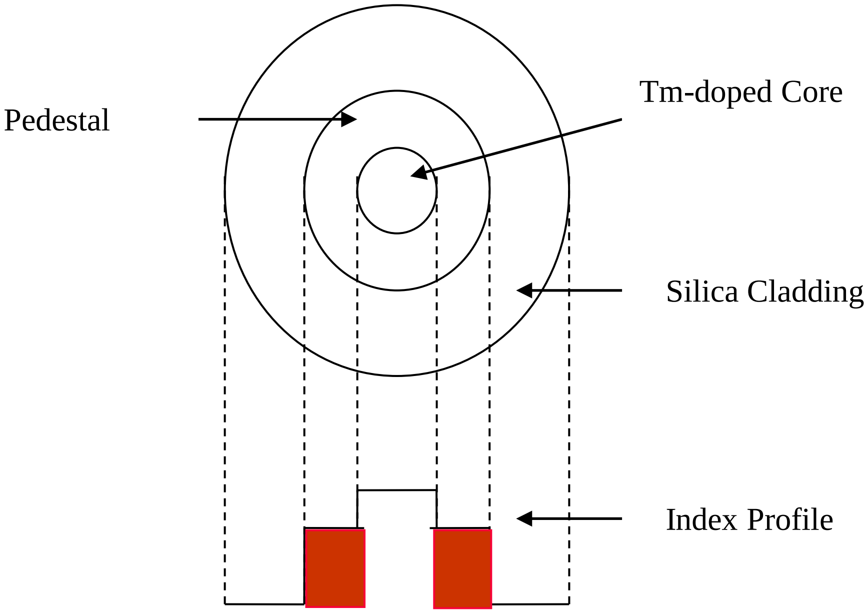


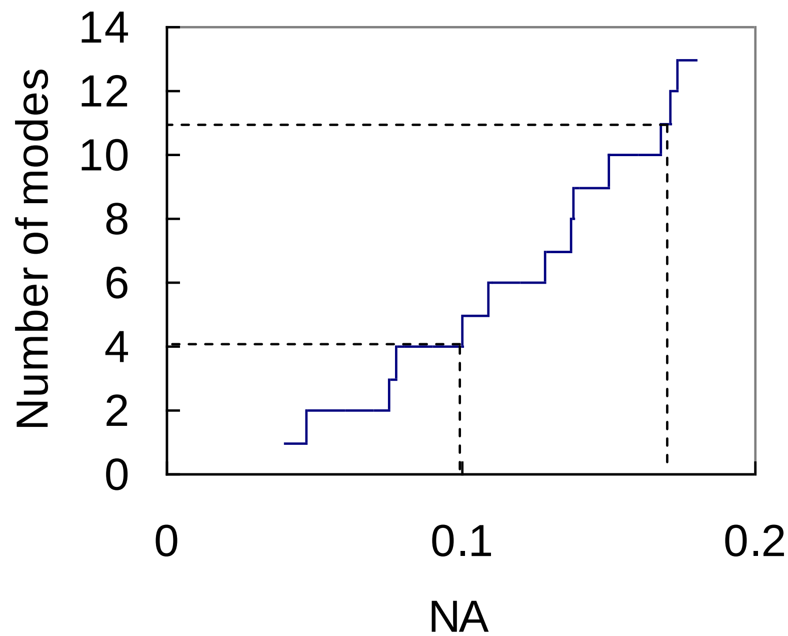


High Tm-doping levels coupled with high Al co-dopant levels would lead to an NA>0.2 w.r.t. the silica cladding

(A. Carter et al., CLEO 2007)

Tm-doped LMA Fibers for Single Mode Beam Quality

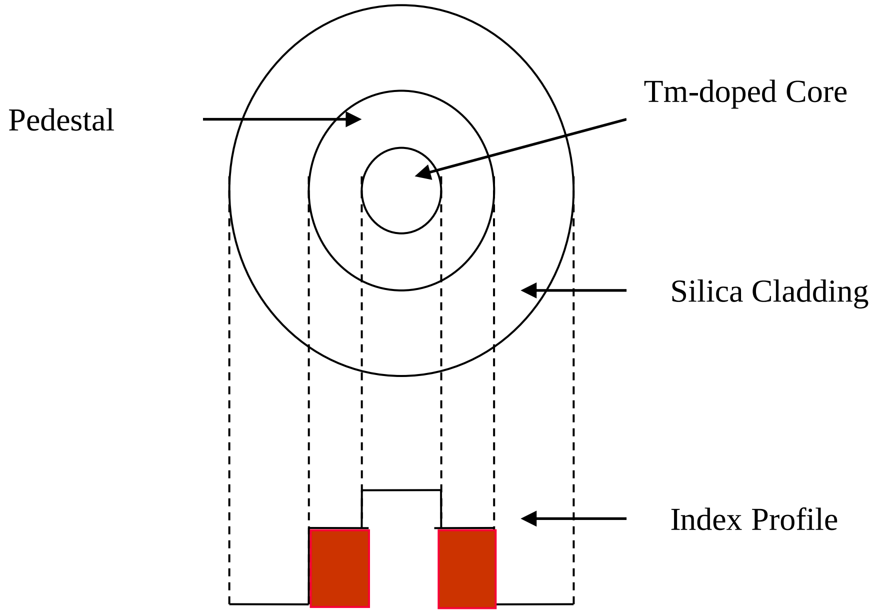


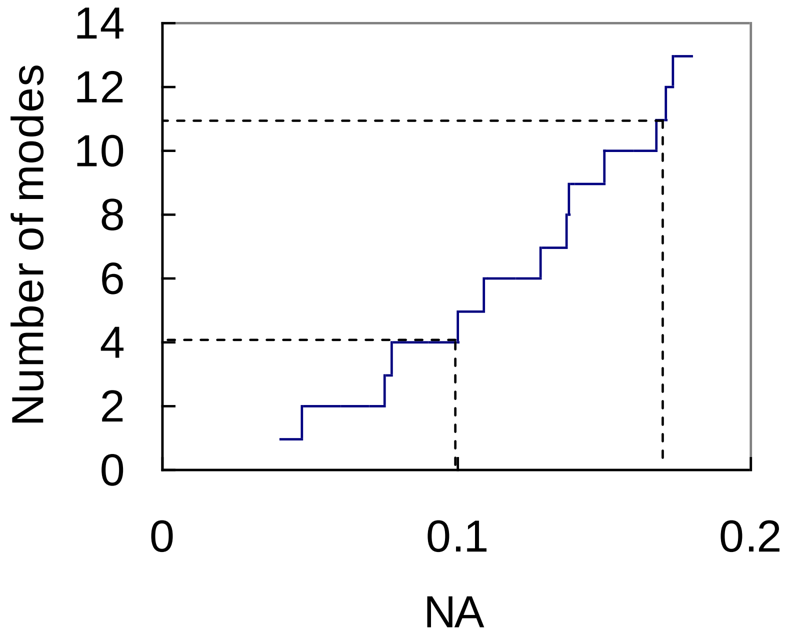


By incorporating a pedestal layer around the Tm-doped core the effective NA is reduced to ~0.1, reducing the mode content within the doped core

(A. Carter et al., CLEO 2007)

Tm-doped LMA Fibers for Single Mode Beam Quality

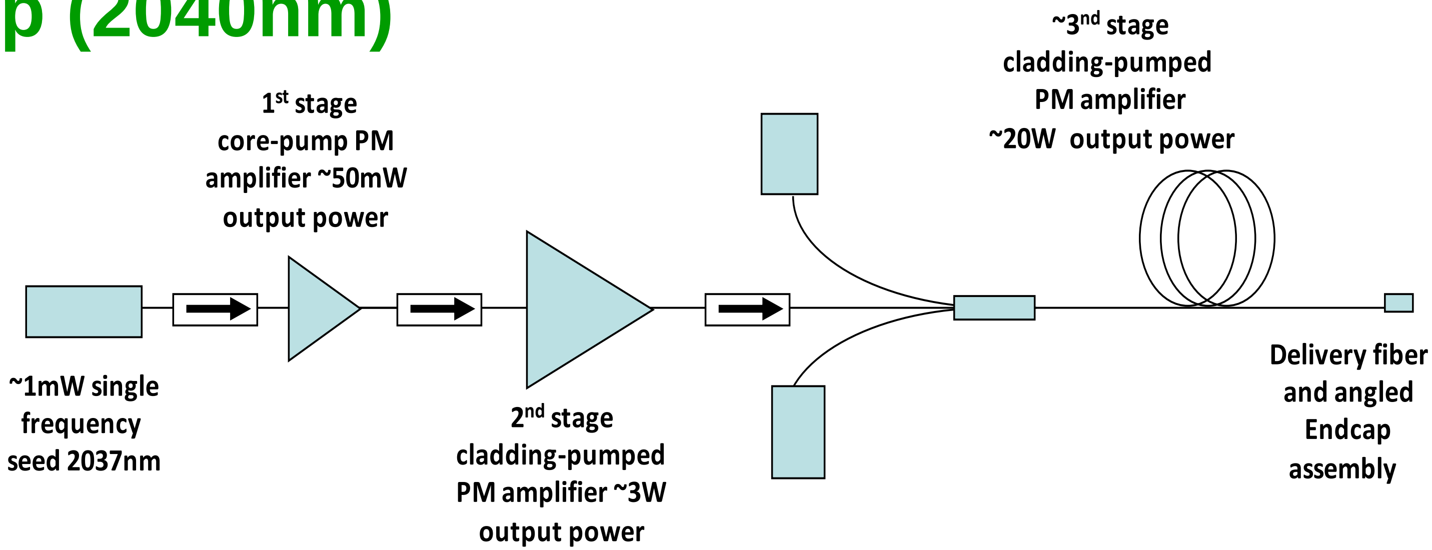




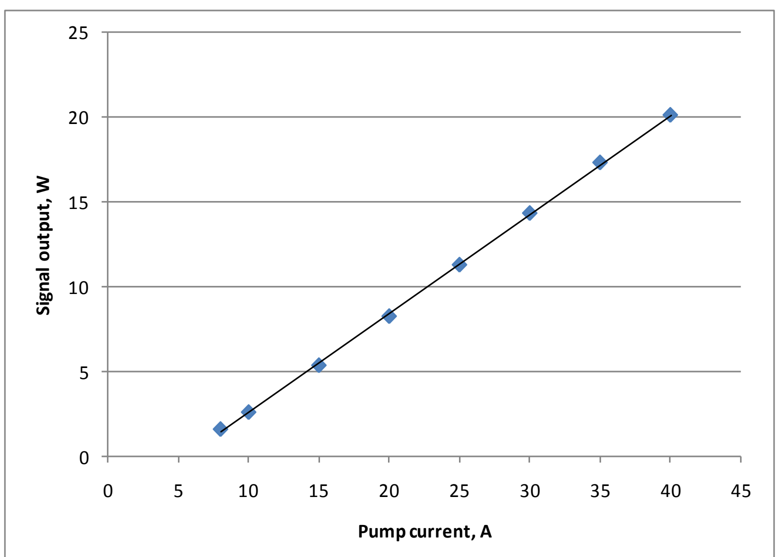
By reducing the NA of the core, large core fibers with good beam quality became possible (LMA fibers)

(A. Carter et al., CLEO 2007)

Monolithic 20W Single Frequency PM Amp (2040nm)



- PM Isolator



Monolithic 3-stage (20W) PM amplifier compatible with input from semiconductor DFB diode at 2µm (~1mW)

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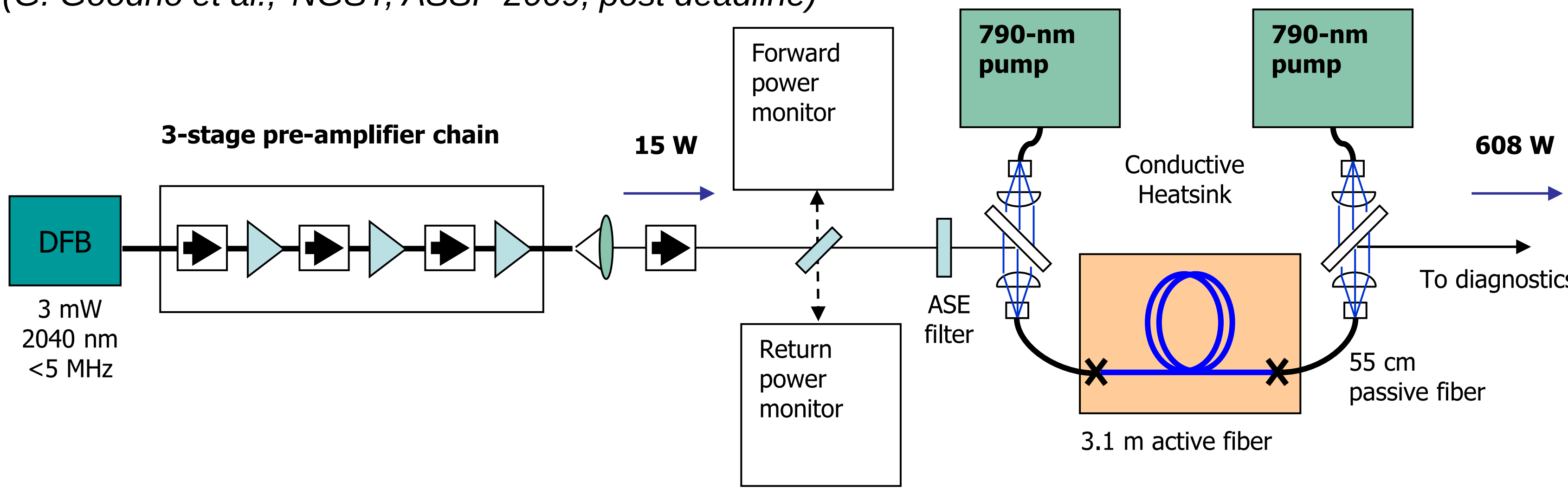
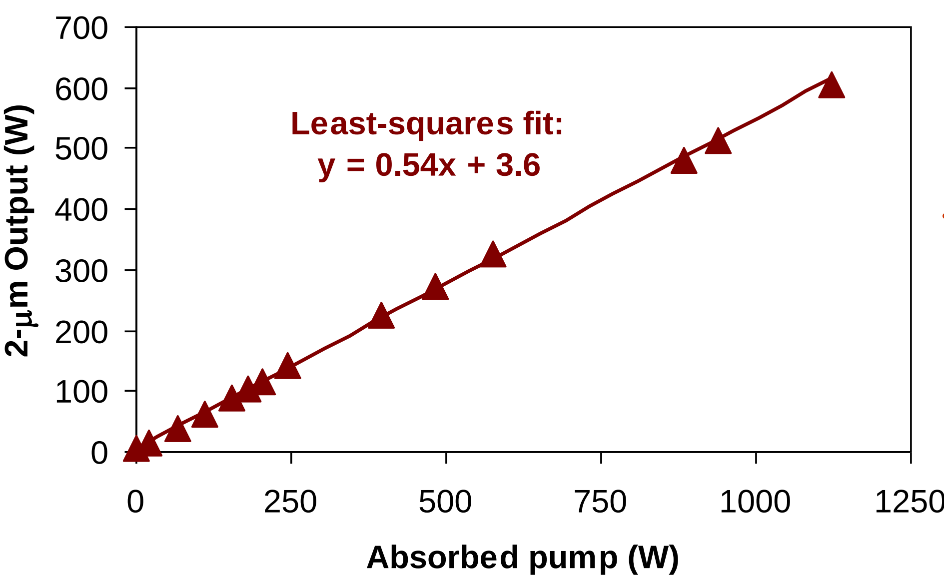
High Power Single Frequency at 2μm
600W single frequency amplifier

(G. Goodno et al., NGST, ASSP 2009, post deadline)





600W result is based on 3.1m of Tm-LMA 25/400 fiber and is not an SBS limited result at this power

NORTHROP GRUMMAN

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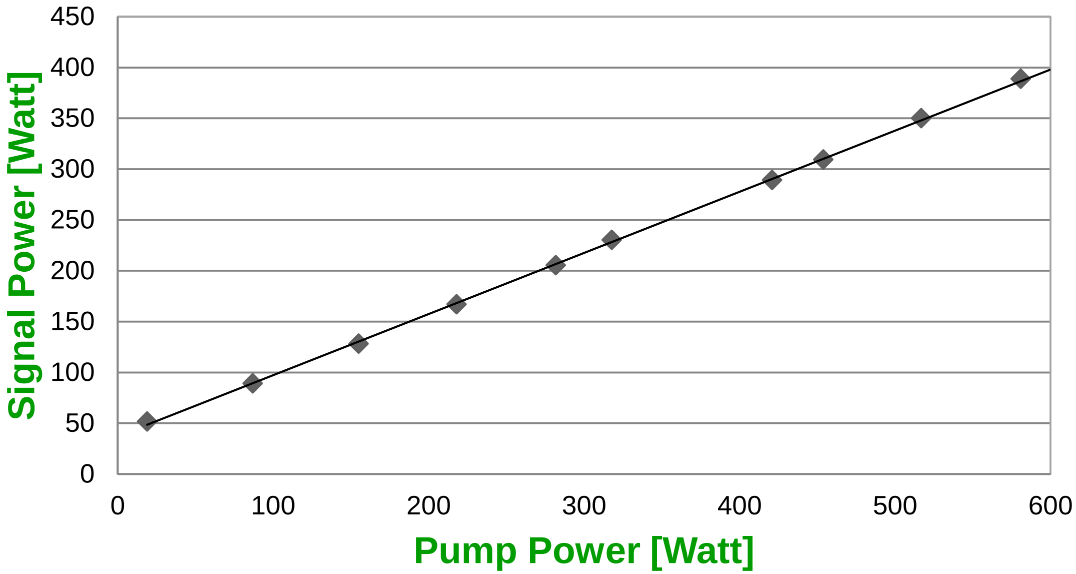
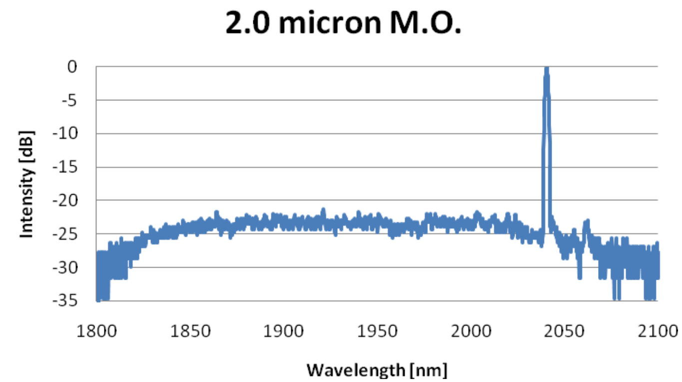
Monolithic 400W Single Mode MOPA at 2040nm

2040nm Power vs. 790nm Pump Power





System is based on Tm-LMA-20/400 was delivered to US Government lab June 2009

RGB Harmonics from Fiber NLLs

(Reference, J. Anderegg et al, SPIE Photonics West, 2010)

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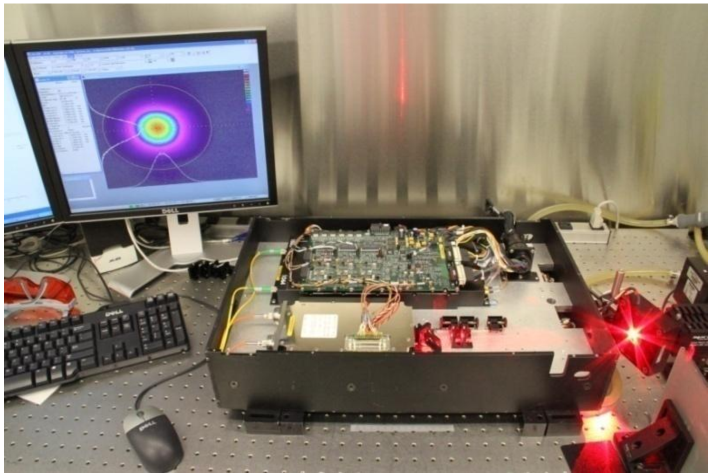
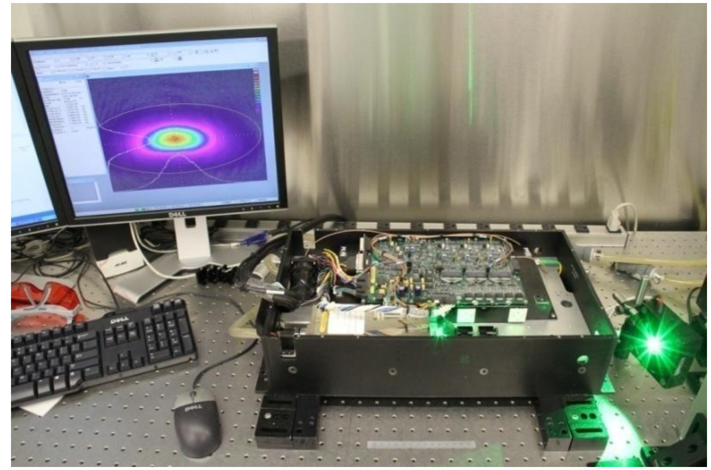
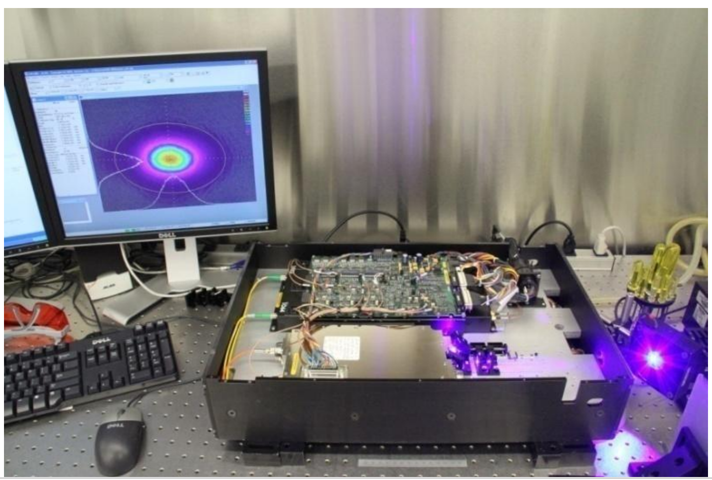
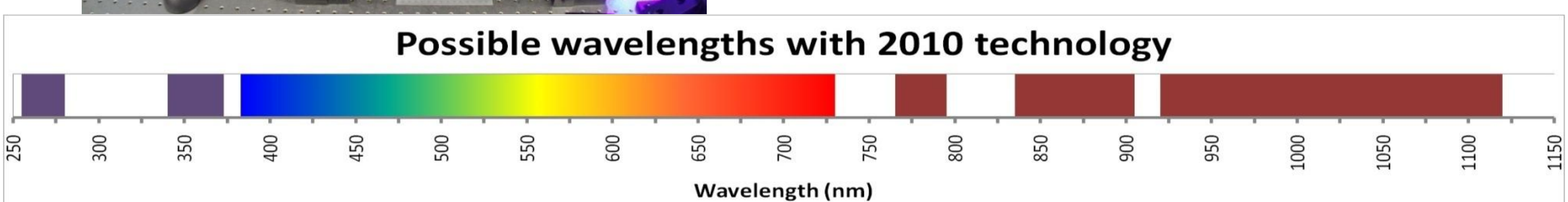




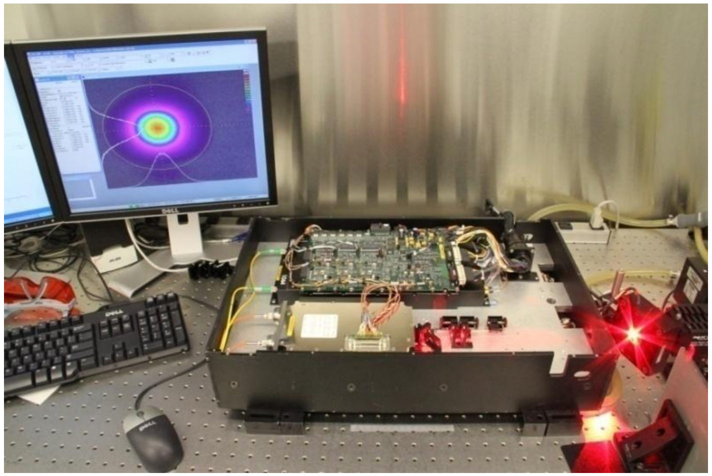


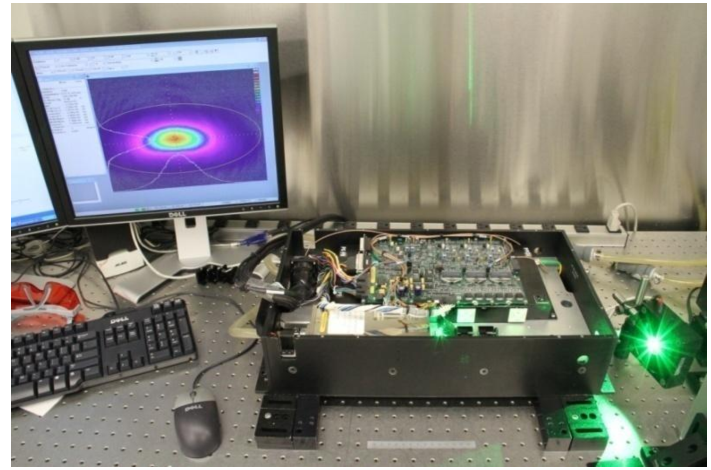
Through the 2nd and even the 3rd harmonics of the 1um, 1.5um and 2um narrow linewidth lasers provide narrow linewidth laser source in visible regime.

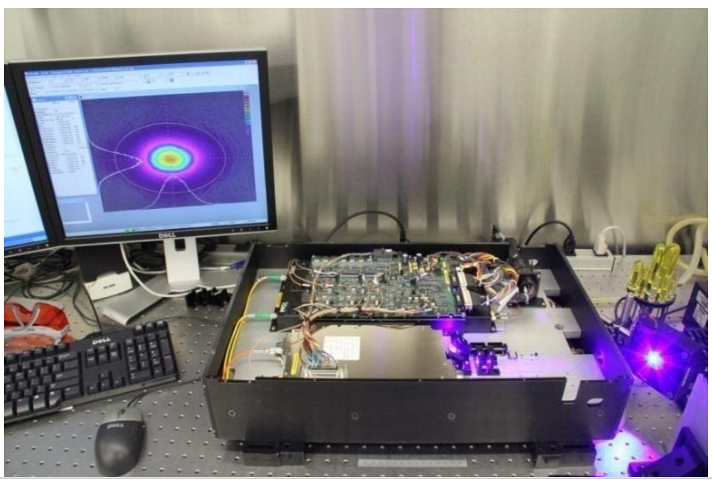


RGB Harmonics from Fiber NLLs

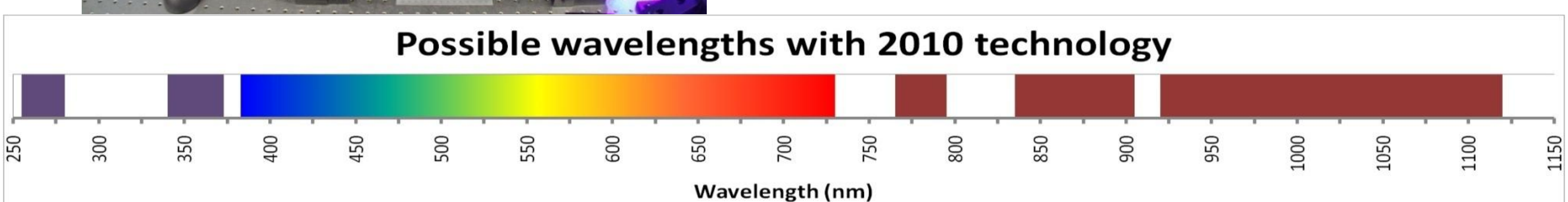
(Reference, J. Anderegg et al, SPIE Photonics West, 2010)







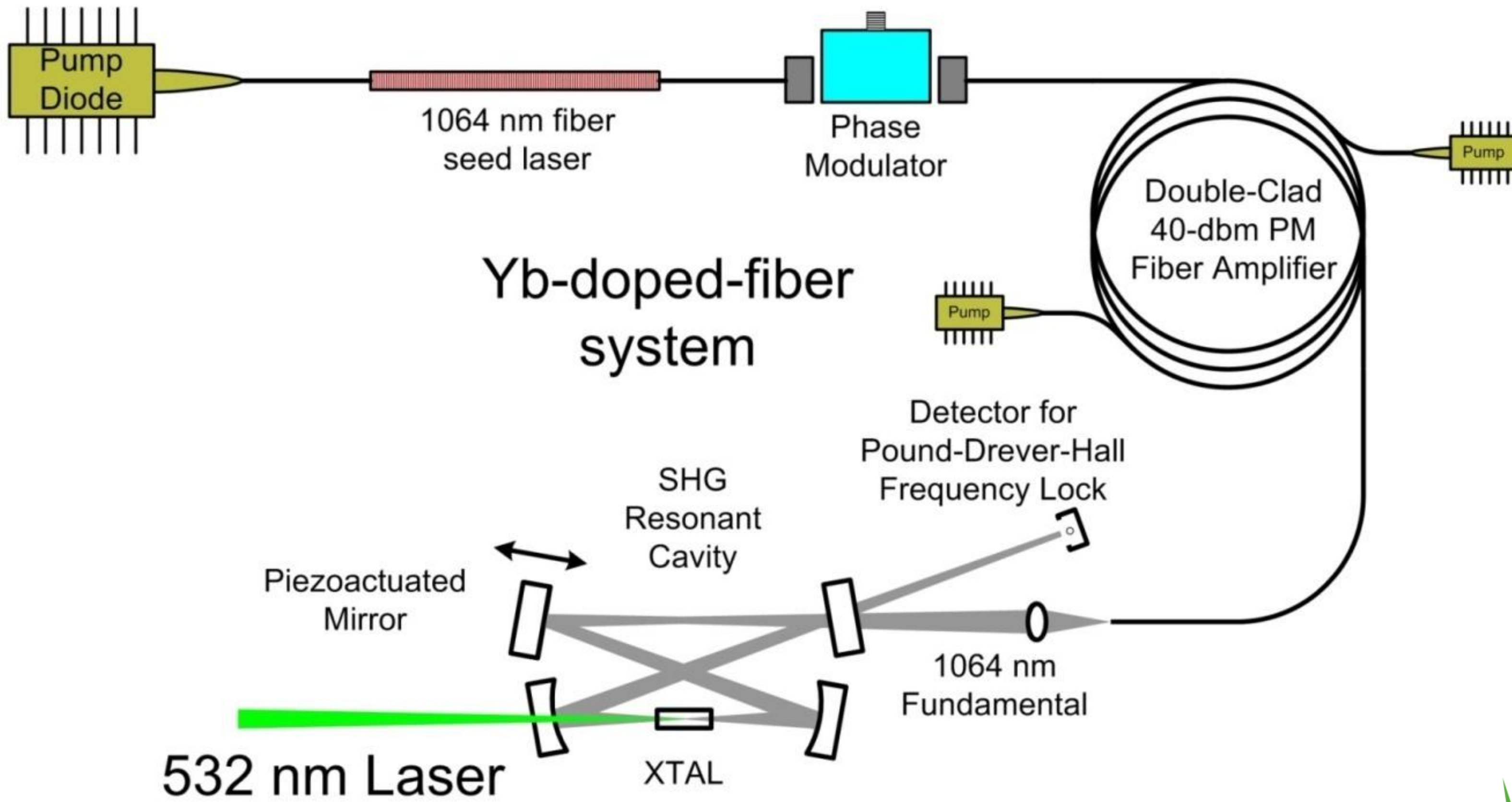
Additional wavelength regime can be produced through the Sum-Frequency Generation (SFG).



Frequency Doubling of High Power Fiber Lasers

(Reference, J. Anderegg et al, SPIE Photonics West, 2010) E&S EVANS & SUTHERLAND

Fiber MOPA coupled to enhancement cavity



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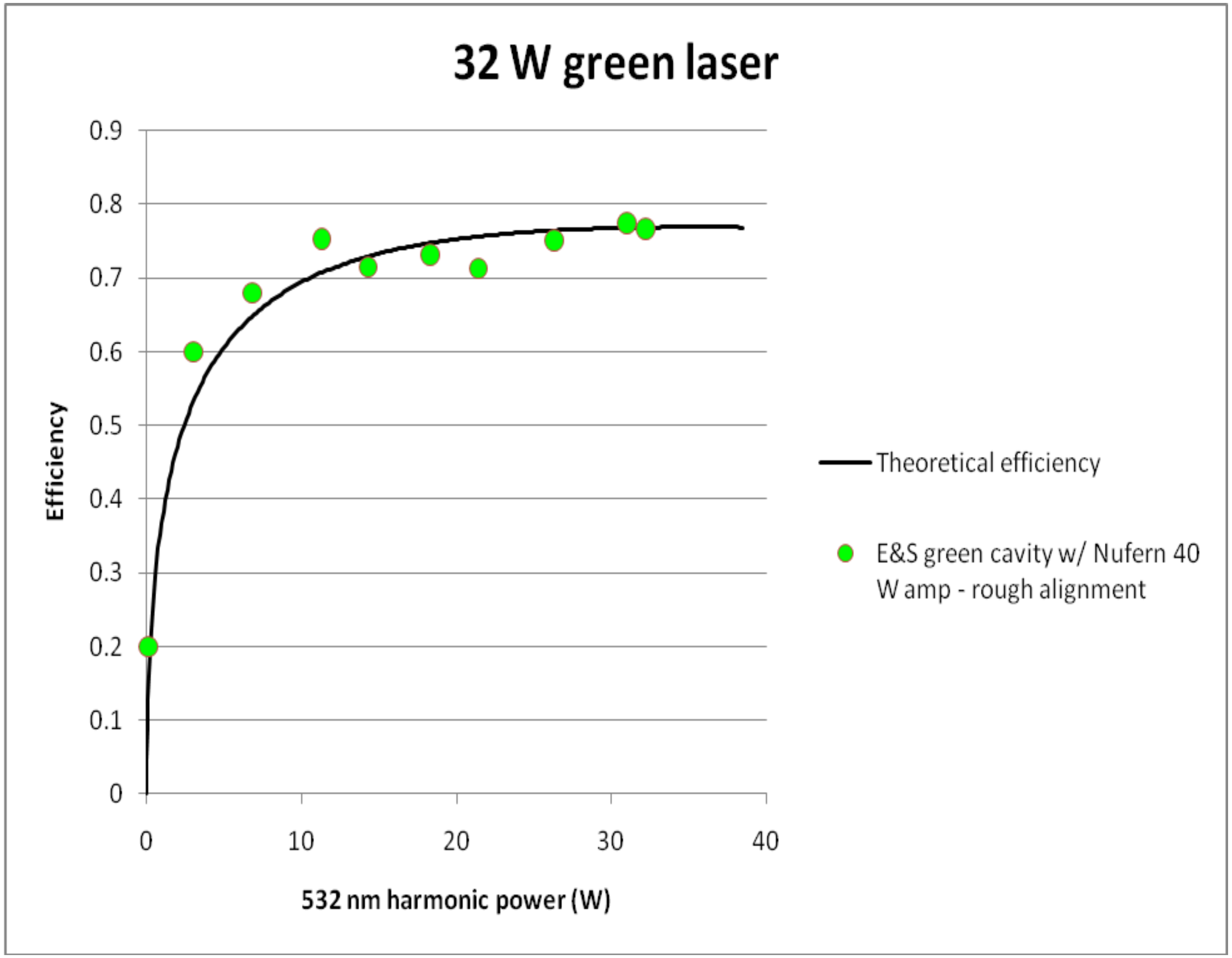

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Conclusion

With the advance in the fiber design and implementation of various SBS mitigation techniques,

- Up to 100W 1.0um single frequency amplifiers (<5kHz linewidth) has been demonstrated.
- Up to 100W 1.5um single frequency amplifiers (<5kHz linewidth) has been demonstrated.
- Up to 600W 2um single frequency amplifiers (3MHz linewidth) has been demonstrated.

Conclusion

Together with the advance in the harmonic conversion cavities, these high power narrow linewidth fiber amplifiers can provide a broad range of narrow linewidth lasers targeting various atomic transition band.

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