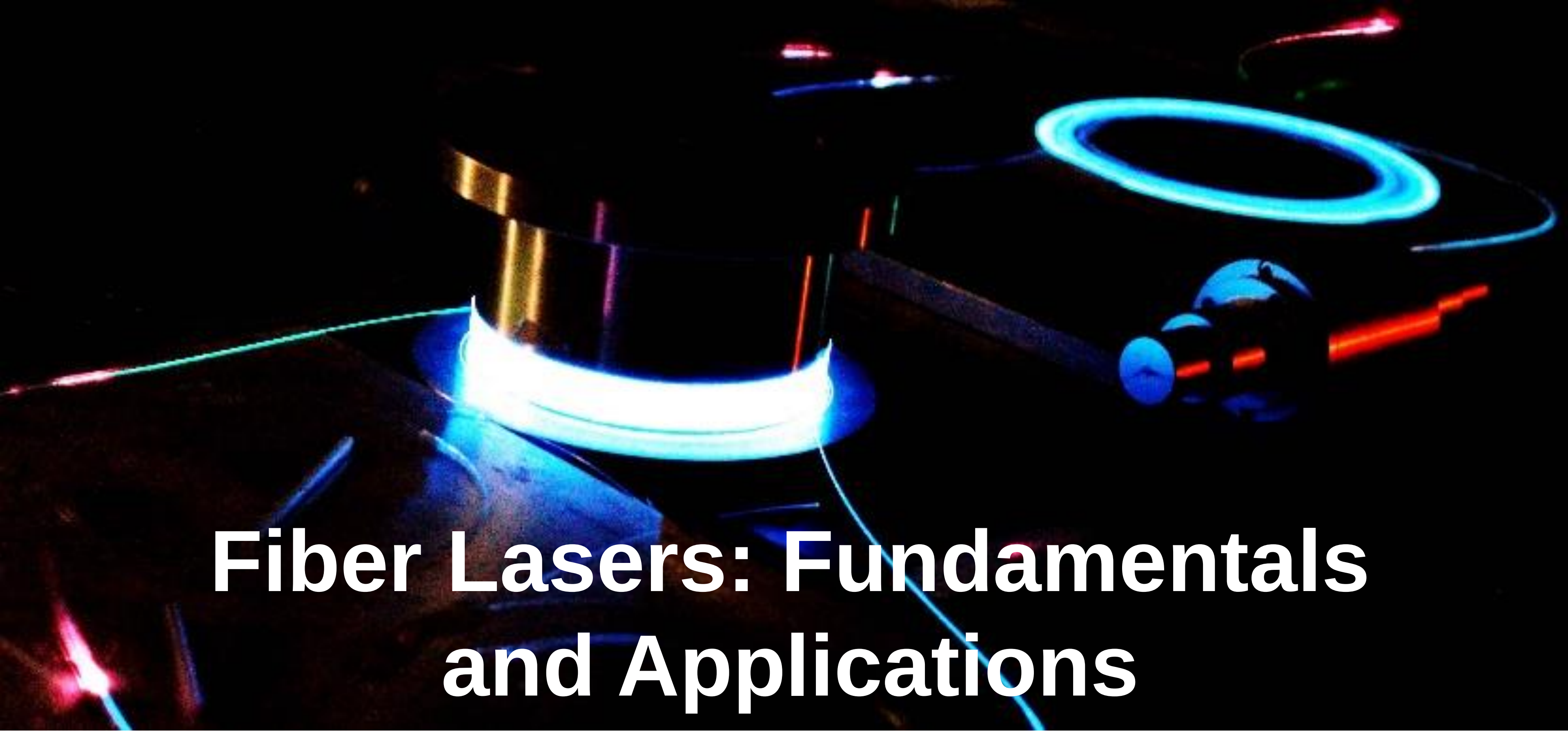

Fiber Lasers: Fundamentals and Applications

Lecture 5

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Indian Institute of Science

Source Material

New review paper: V R Supradeepa, Yan Feng, Jeffrey W. Nicholson, "Raman Fiber Lasers," IOP Journal of Optics (2017). Please refer to the paper for exact references to material shown in this lecture

Raman fiber lasers

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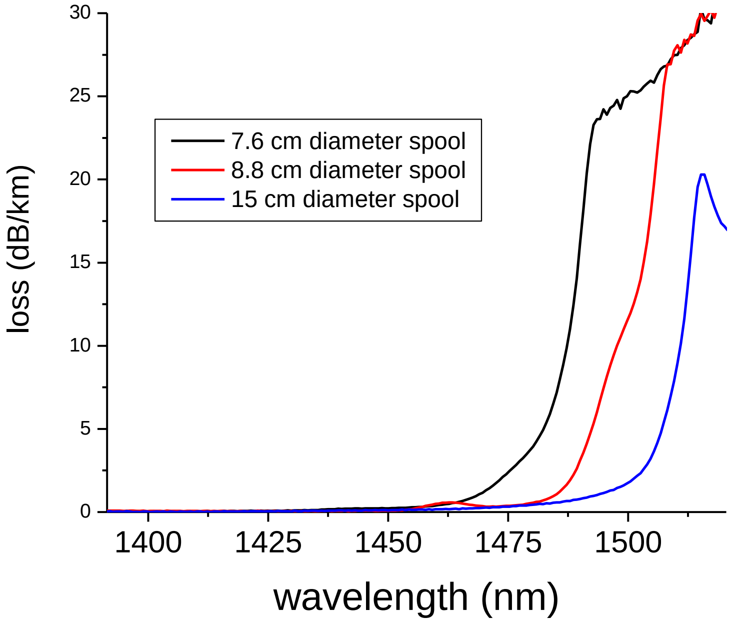
Abstract

High-power fiber lasers have seen tremendous development in the last decade, with output powers exceeding multiple kilowatts from a single fiber. Ytterbium has been at the forefront as the primary rare-earth-doped gain medium owing to its inherent material advantages. However, for this reason, the lasers are largely confined to the narrow emission wavelength region of ytterbium. Power scaling at other wavelength regions has lagged significantly, and a large number of applications rely upon the diversity of emission wavelengths. Currently, Raman fiber lasers are the only known wavelength agile, scalable, high-power fiber laser technology that can span the wavelength spectrum. In this review, we address the technology of Raman fiber lasers, specifically focused on the most recent developments. We will also discuss several applications of Raman fiber lasers in laser pumping, frequency conversion, optical communications and biology.

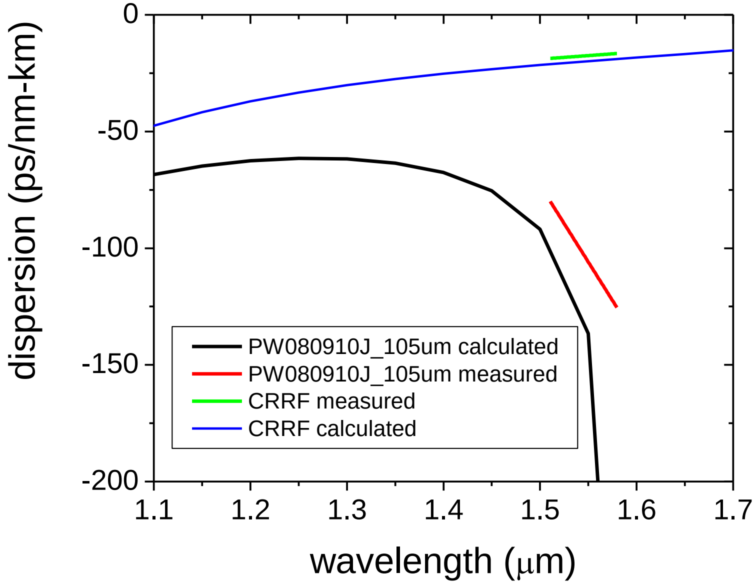
Recent Developments in Cascaded Raman Lasers

Raman Filter fiber and Isolation

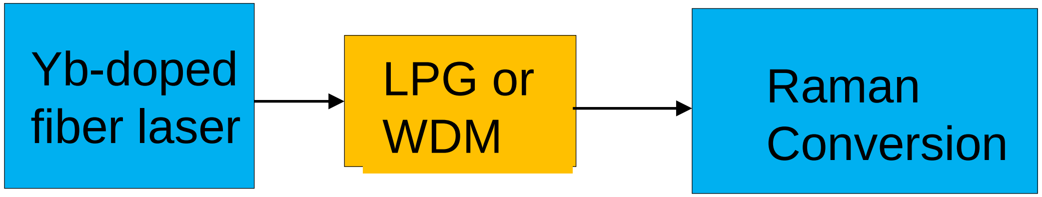
Cut-off



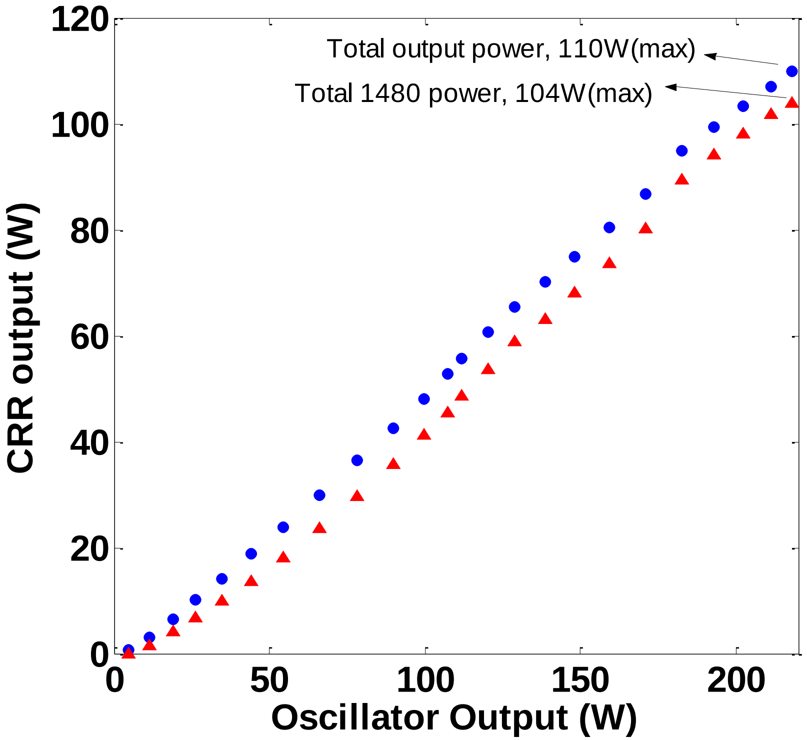
Dispersion

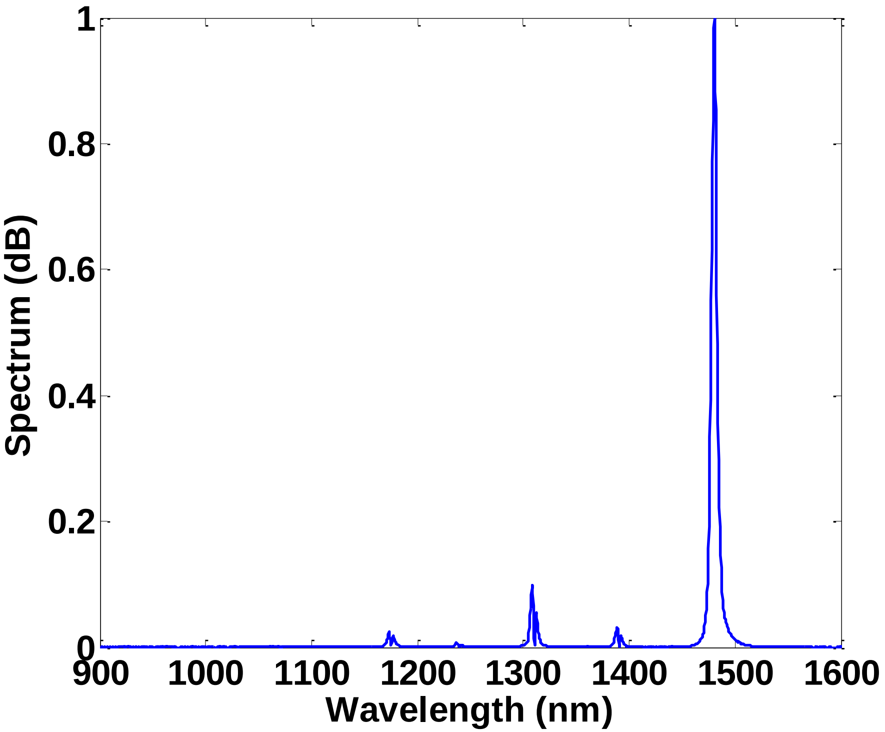


Filter fiber has a cut-off at around 1500nm and Aeff ~15micron^2



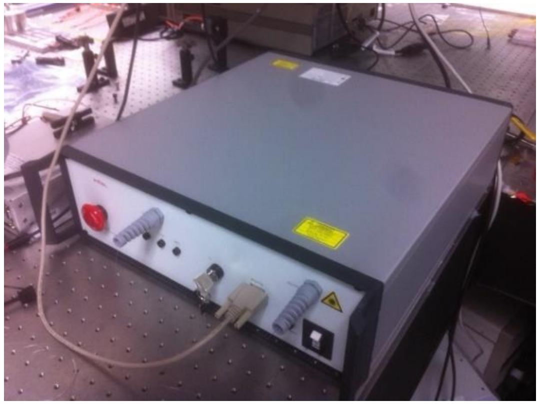
100W Cascaded Raman Laser





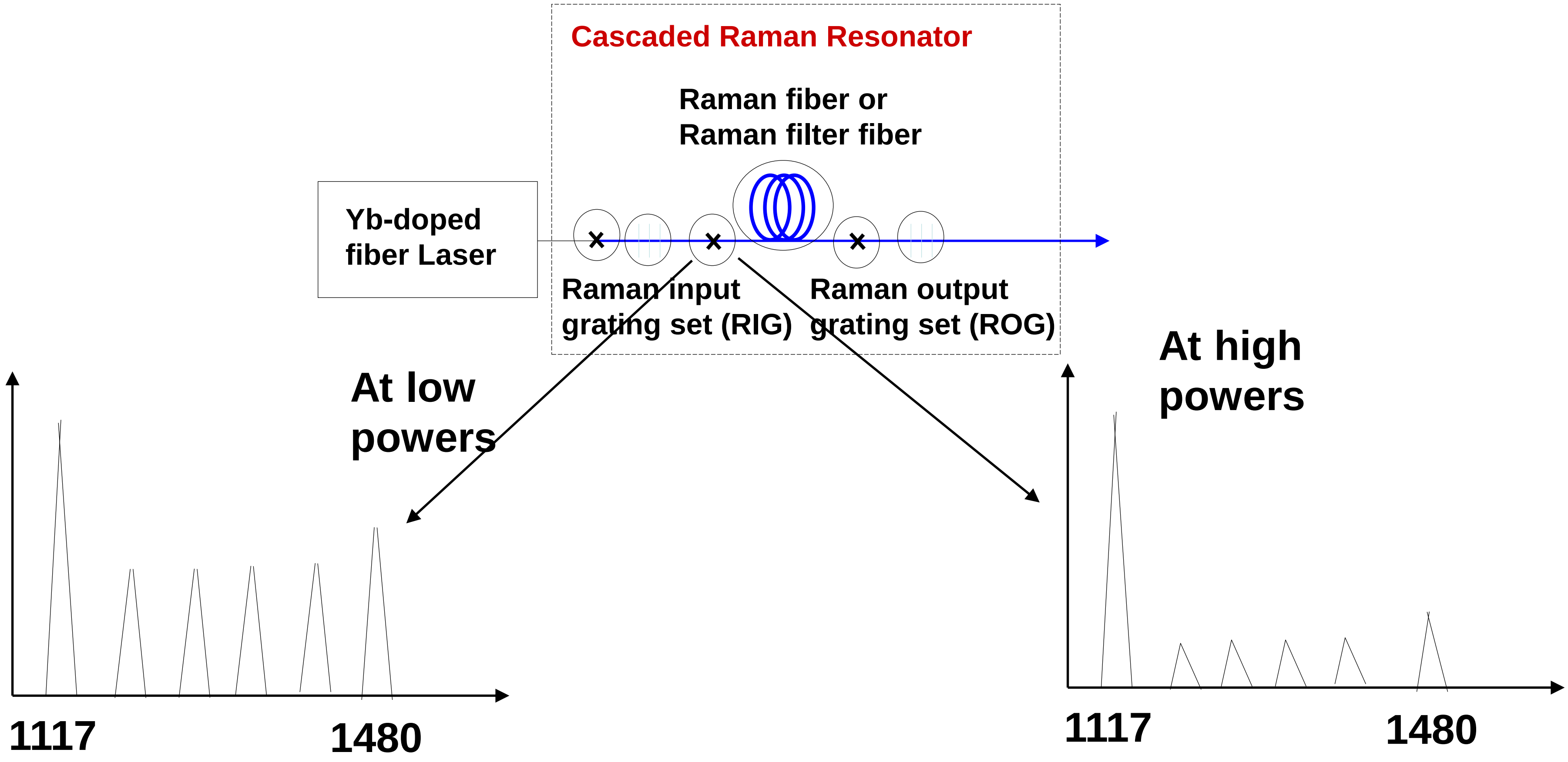
- **Fraction of power in 1480 light ~ 95%**
- **Total conversion efficiency to 1480nm light ~ 48%**
- **Can we further improve this ?**

V R Supradeepa et al, Photonics West (2012)



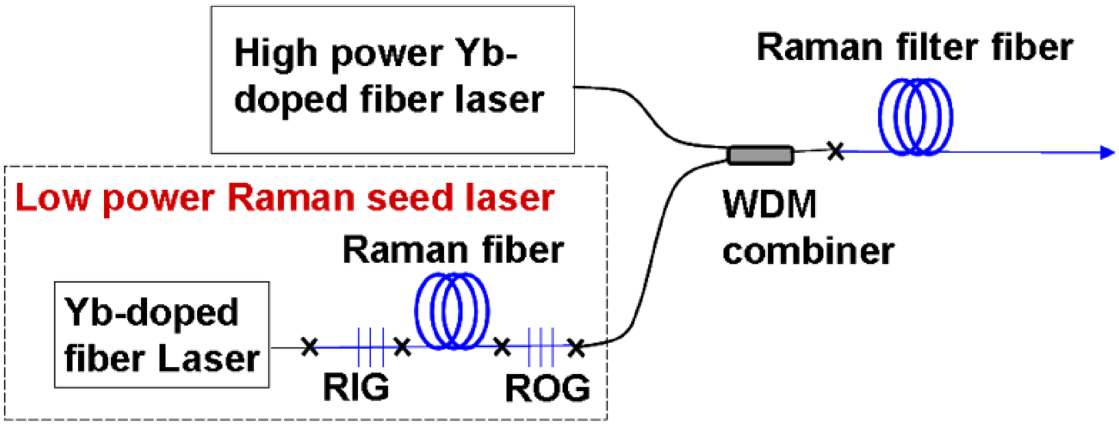
Enhanced Efficiency Cascaded Raman Lasers

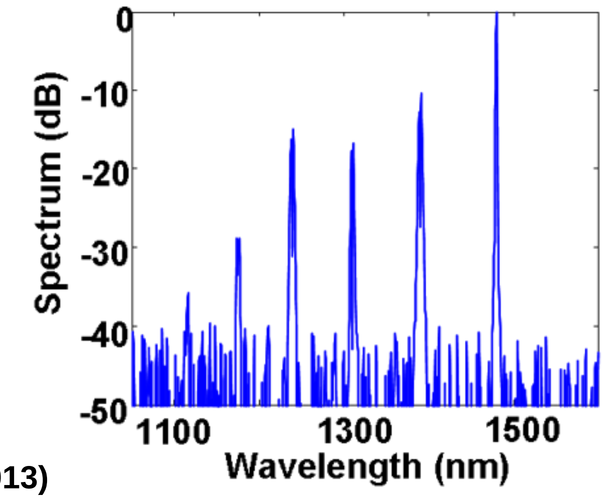
- Quantum limited conversion efficiency from 1117nm to 1480nm = 75%
- Current laser provides ~48%.



V R Supradeepa et al, Optics Express (2013)

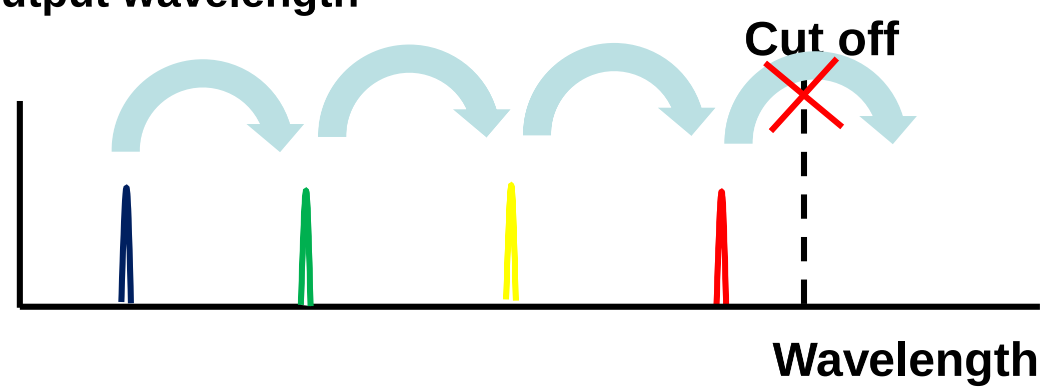
Cascaded Raman amplifier architecture

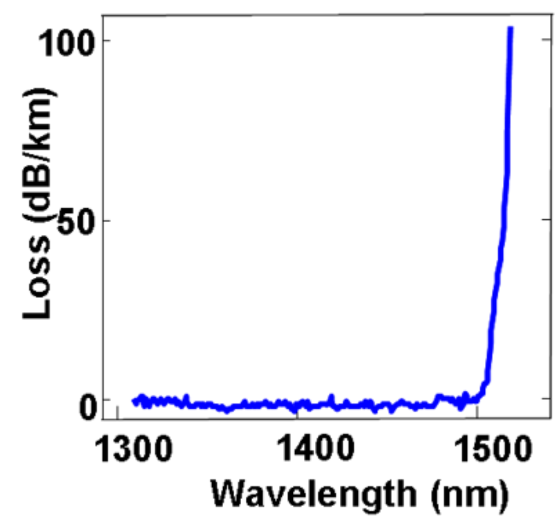




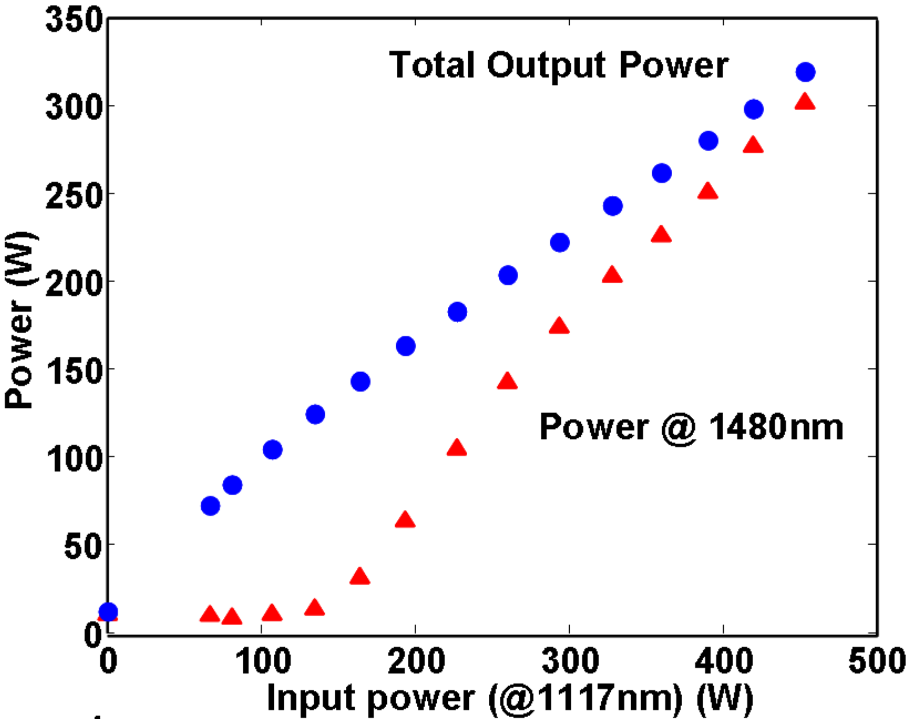
V R Supradeepa et al, Opt Exp (2013)

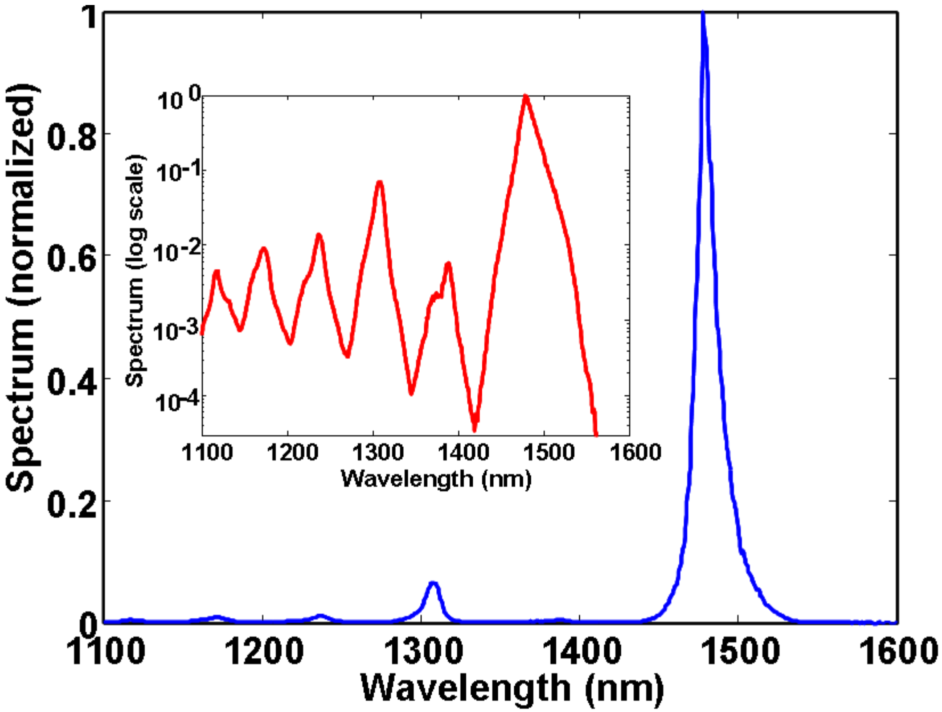
- A lower power conventional cascaded Raman laser provides all the intermediate seed wavelengths.
- Filter fiber is used to terminate the cascade at the desired output wavelength





Results





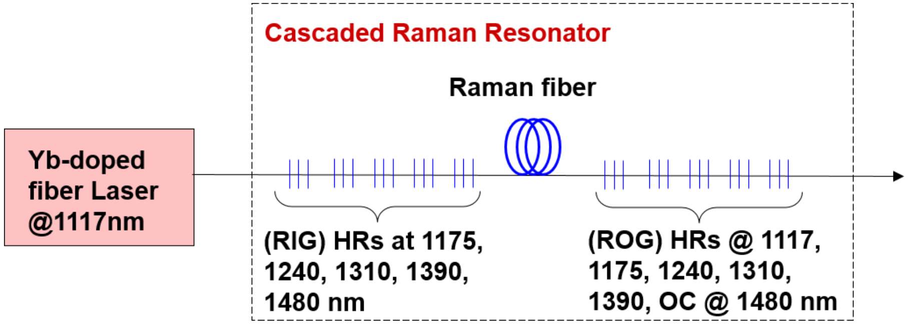
V. R. Supradeepa, J. W. Nicholson, Optics Letters 2013

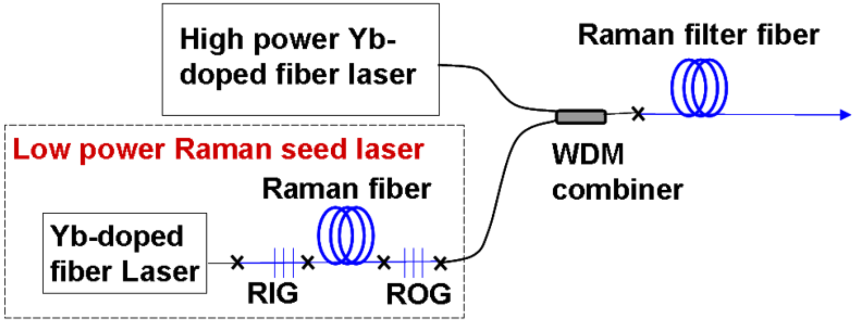
Output power of 301W at 1480nm for input power of 453W at 1117nm

Conversion efficiency from 1117nm to 1480nm ~ 65 % (Q. E. 75 %)

Highest power from any laser technology in the eye safe 1.5micron region

Moving to a simpler architecture



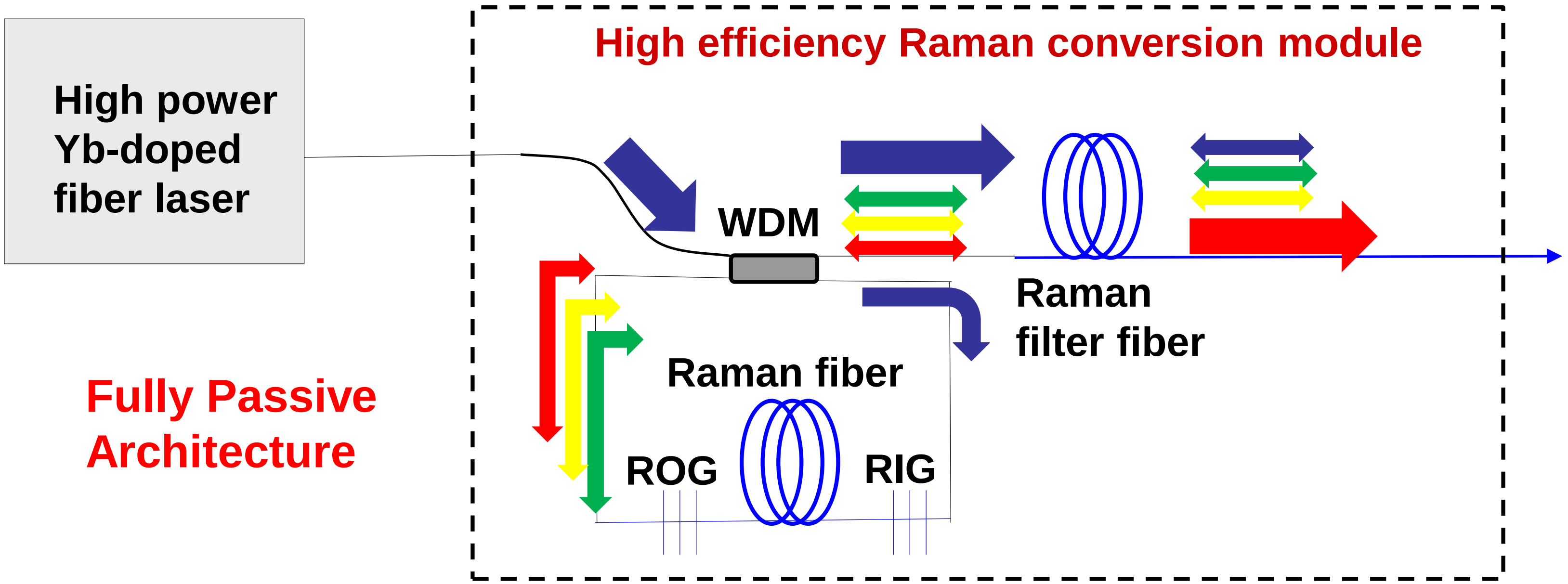


- Architecture – Passive (Simpler)
- Efficiency – Low
- Reliability - low

- Architecture – Active (complex)
- Efficiency – High
- Reliability - High

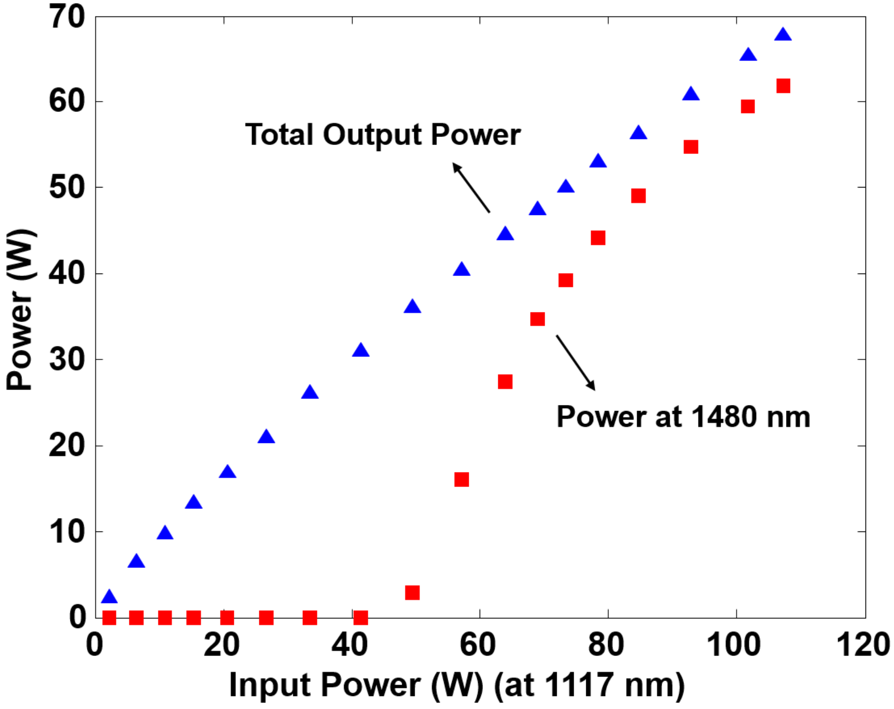
It is desired to have an architecture which combines the positives of both designs – i.e Achieve high efficiency in an all passive architecture

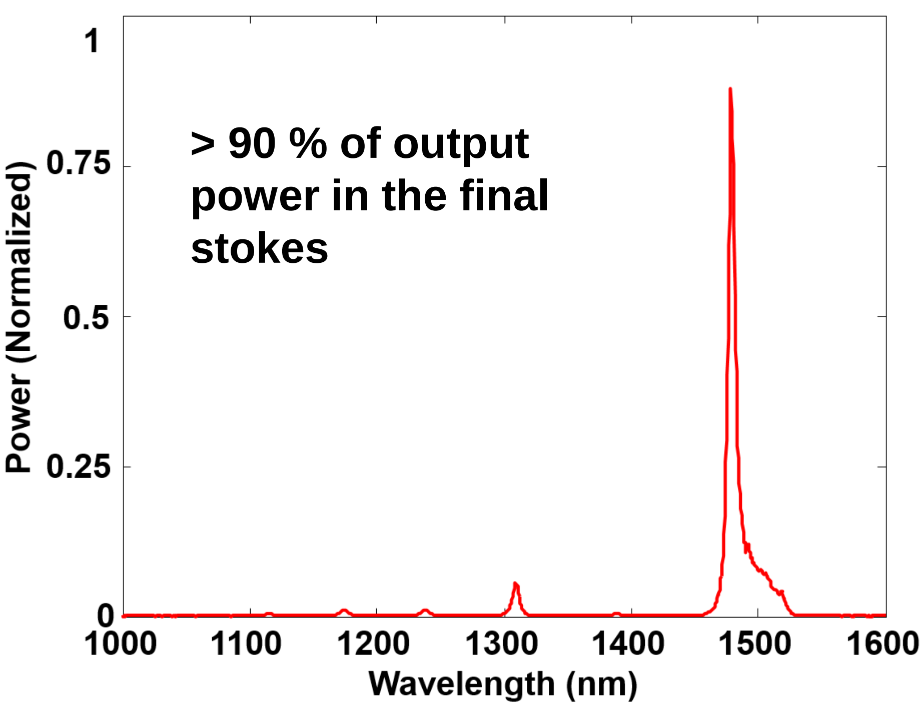
Simplified amplifier architecture



- A small fraction of light is tapped by the leakage (cross-talk of WDM)
- This is used to generate the seed wavelengths needed for conversion
- Filter Fiber terminates the cascade
- Important - feedback of backward light from Raman gratings

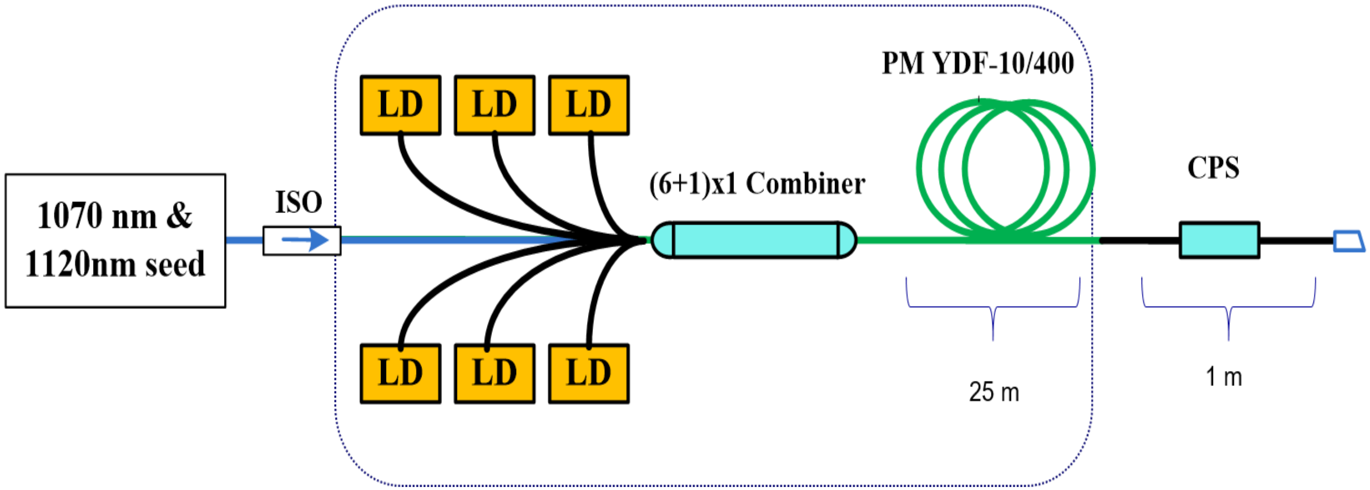
Simplified Architecture - Results





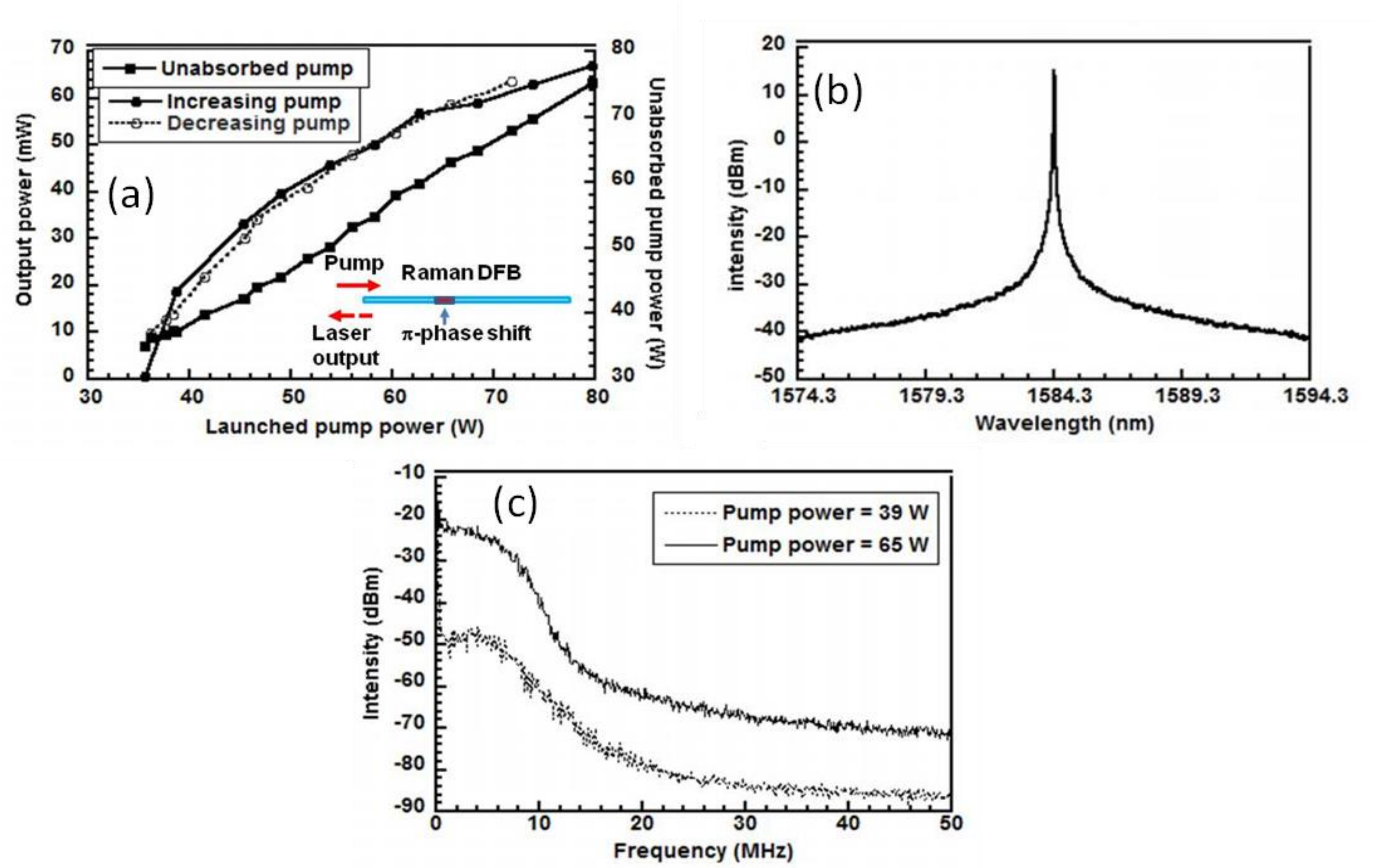
- Experiment – Yb Laser - 107W at 1117nm, ~250m of Raman filter fiber, Aeff = 15 μm^2
- Output 1480 power @full current ~ 64 W
- Limited only by pump power
- Conversion efficiency from 1117nm to 1480nm ~ 60 % (Q. E. 75 %)

Hybrid Rare-earth Raman Fiber Lasers



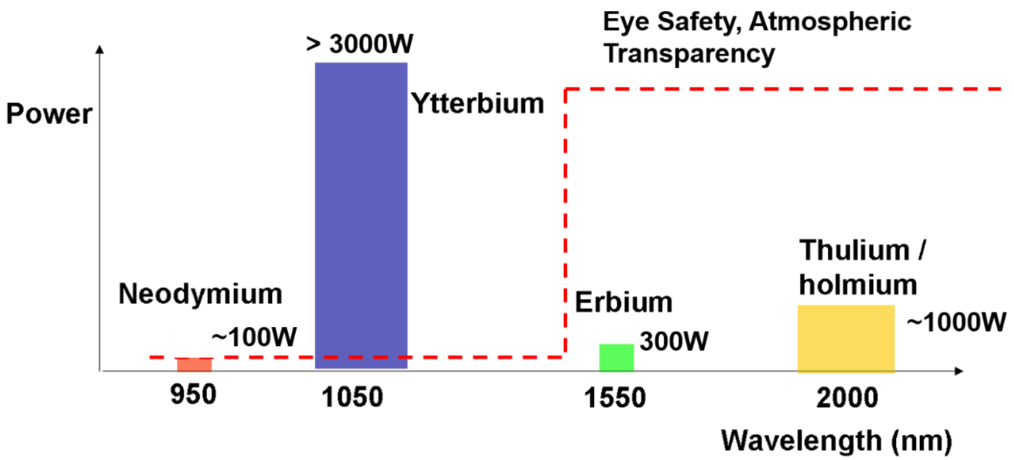
Upto 1.5kW of power has been achieved using this technique

Raman DFB Fiber Lasers



Over 50mW achieved with a narrow linewidth of 6MHz

What do we have ?

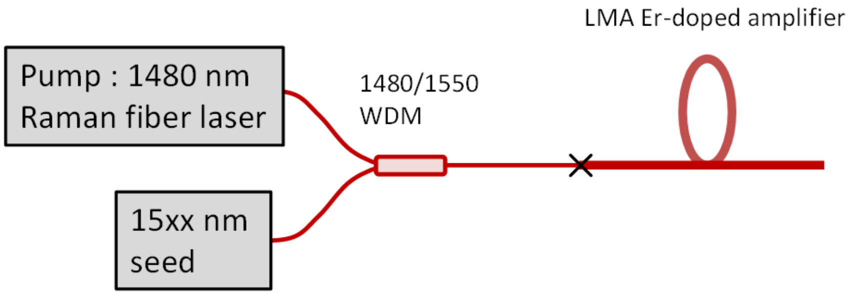


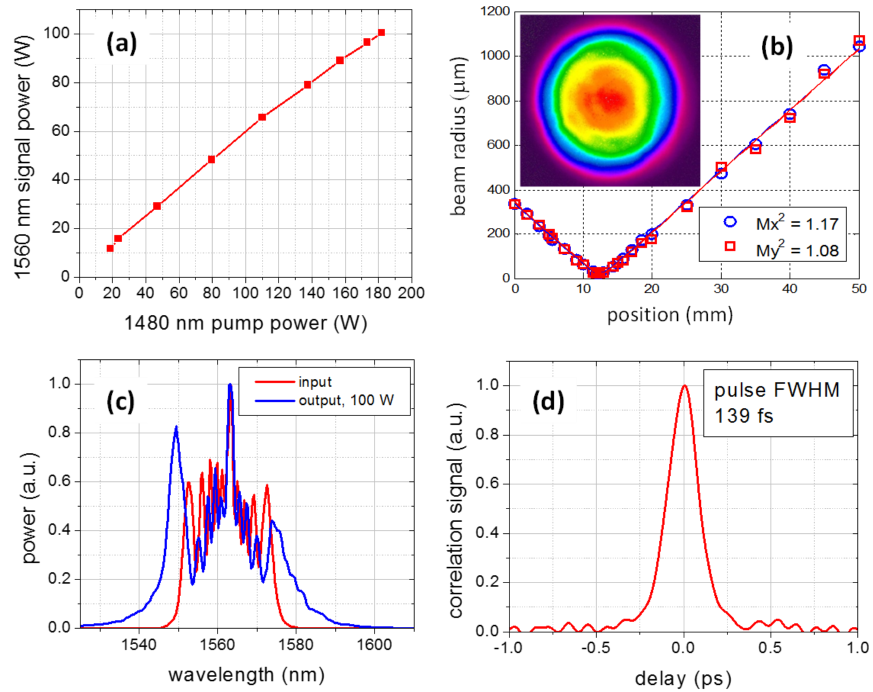
A scalable method to achieve high power levels at arbitrary wavelengths !

Some Applications of Raman Lasers

Raman Fiber Lasers for Optical Pumping

Core (high brightness) and in-band pumping of Erbium doped pulsed amplifiers



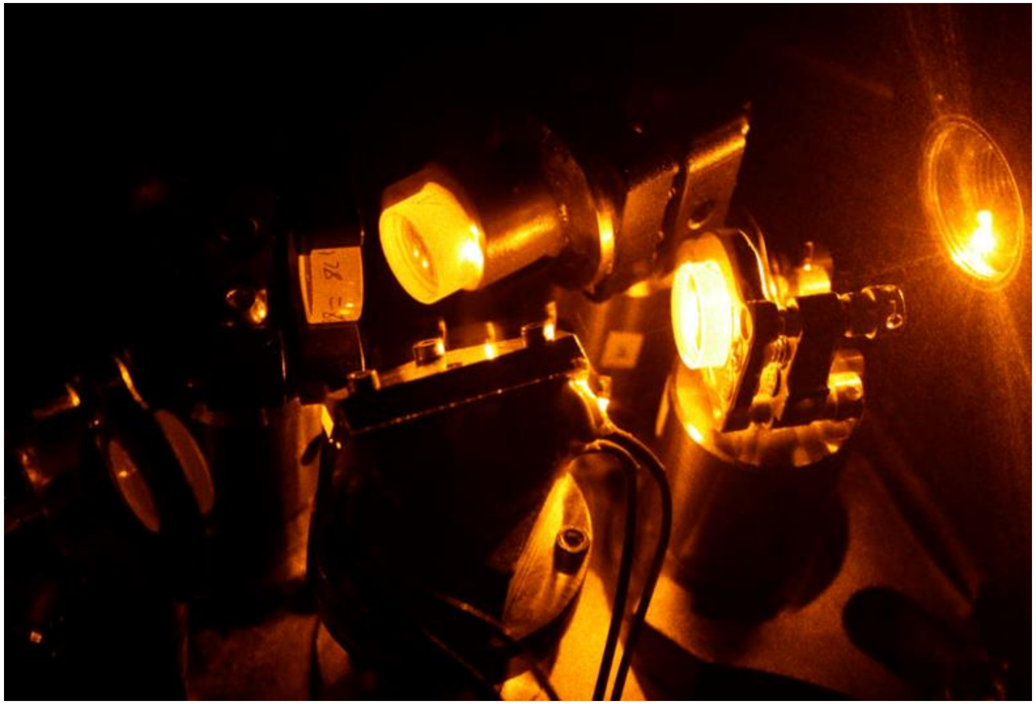


- **In narrow-linewidth CW mode – demonstrated 100W class Yb-free Erbium fiber Lasers** **(Supradeepa et al, CLEO 2012)**

- **Pulsed mode – Recent demonstrations of mJ class nanosecond pulses (MW peak powers)** **(Nicholson, Supradeepa et al, Optics Express 2012)**

Core (high brightness) pumping of Thulium doped fiber amplifiers at 1590nm or 1135nm.

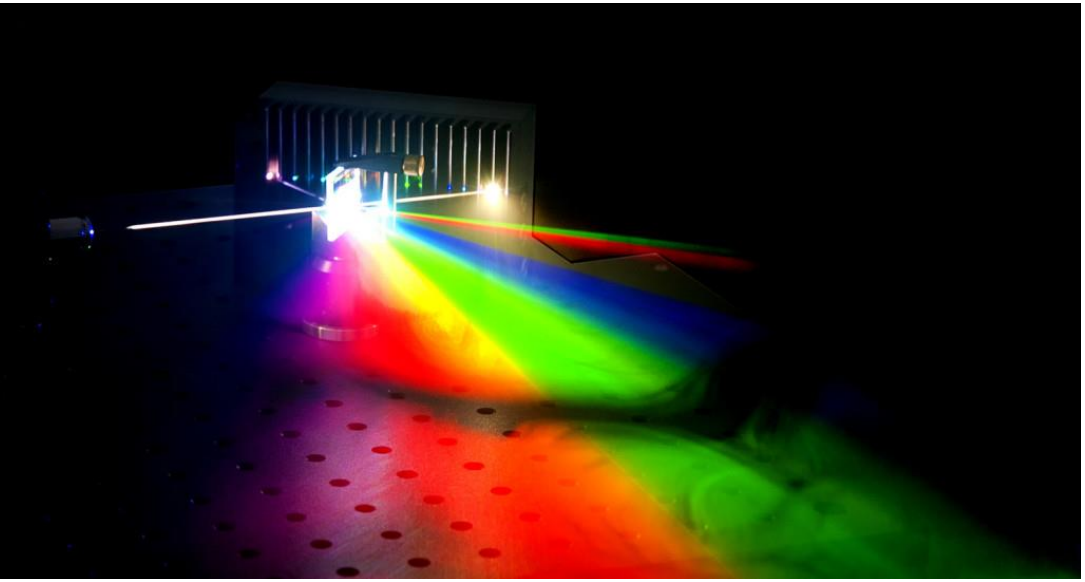
Frequency Conversion of Raman Lasers



- **The wavelength diversity in NIR wavelengths can be leveraged to achieve wavelength diversity in visible by harmonic conversion**
- **589nm Yellow laser by frequency doubling of 1178nm laser (> 50W) – Laser guide stars** **(Yan Feng et al, Optics Letters 2009)**

High Power Continuous Wave Supercontinuum Generation using Raman Lasers

Supercontinuum Lasers



"Broad as a lamp, Bright as a laser"

- **Nobel Prize in Physics (2005) – Laser based Precision Spectroscopy**
- **Nobel Prize in Chemistry (1999) – Femtosecond Spectroscopy**

Biomedical – Optical Coherence Tomography, Super-resolution microscopy

Chemical Sensing – "Spectral Fingerprinting"- Absorption Spectroscopy Drug Detection, Explosives Detection

Communications – THz Laser source in C,L,S wavelength bands

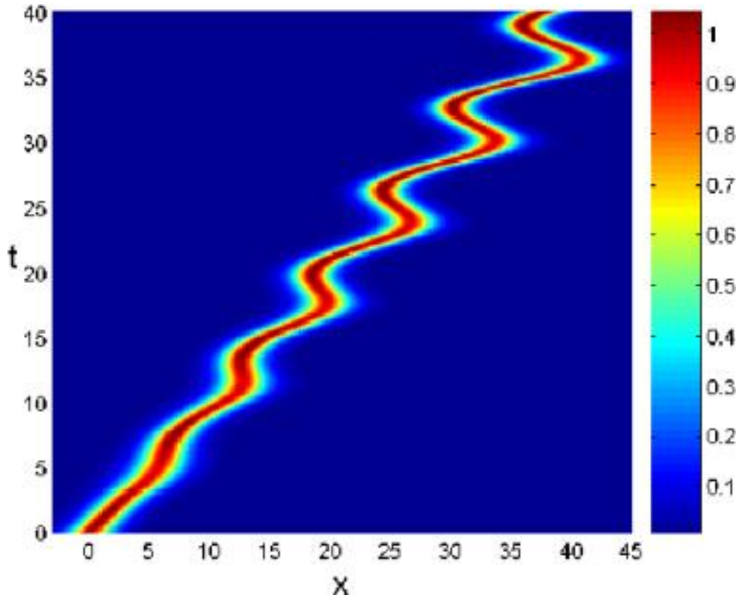
High Power Supercontinuum - Continuous Wave

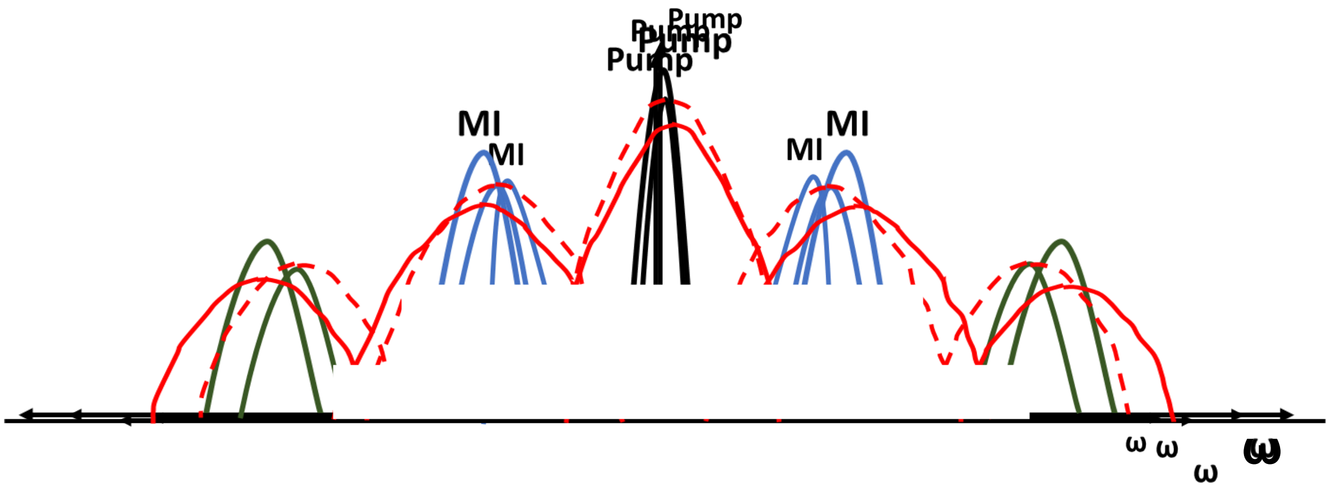
- **High average power(Spectral Density)**
- **Always On-Continuous Output**
- **Less Spectral Power Fluctuations**

Mechanism for CW Supercontinuum Generation

Modulation Instability

- **CW light with sufficient power in anomalous dispersion are inherently unstable**
- **Break into pulses leading to spectral generation**
- **Cause – Interplay between non-linear and dispersive effects**

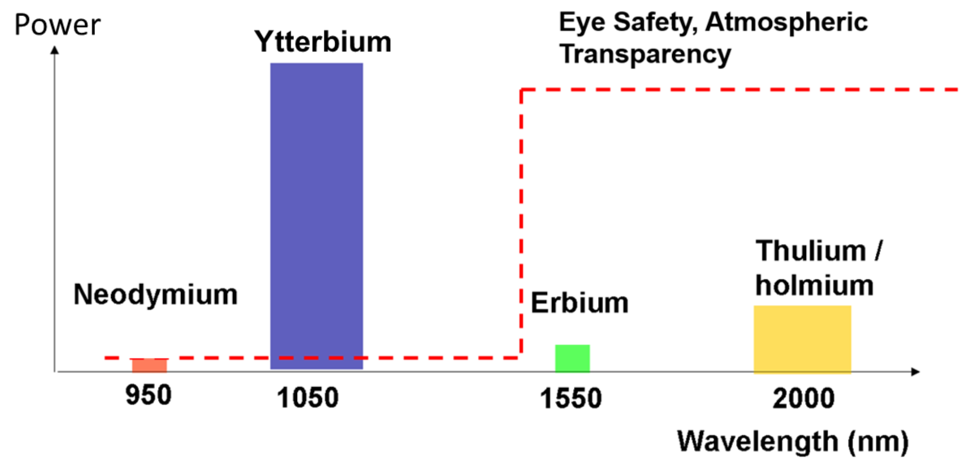




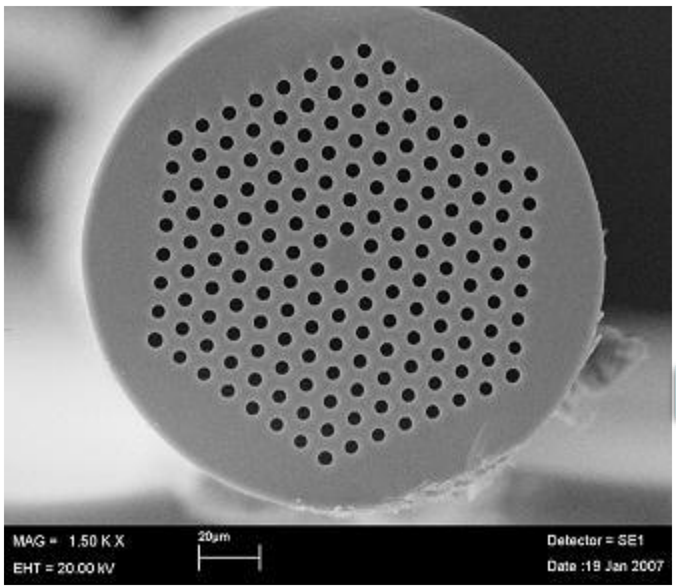
How to Induce Modulation Instability?

Pump in the anomalous dispersion region

Zero dispersion wavelength (λ_0) – For all silica fiber λ_0 > 1300 nm



Lack of robust high power laser source at the desired wavelength (λ_p > 1280 nm)



Limitations

- **i) Difficult to splice**
- **ii) Extremely costly**
- **iii) Free space optics involved**
- **iv) Usually require another pulsed laser**

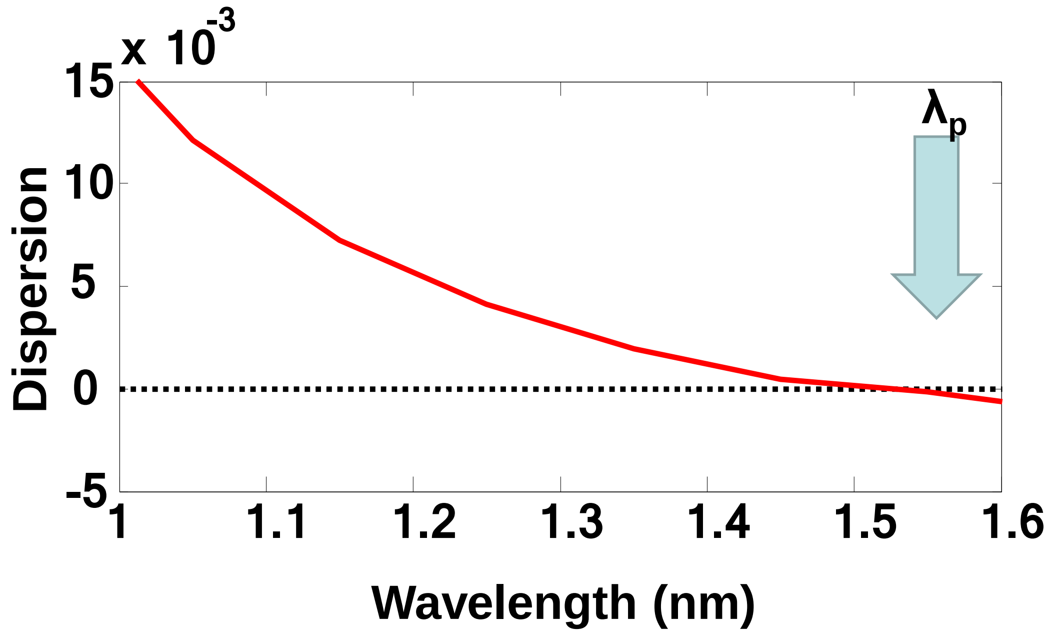
Dispersion can be tailored to be around λ_0 > 1300 nm

Desirable Option

All Silica Fiber Supercontinuum

Highly Nonlinear Fibers (HNLF)

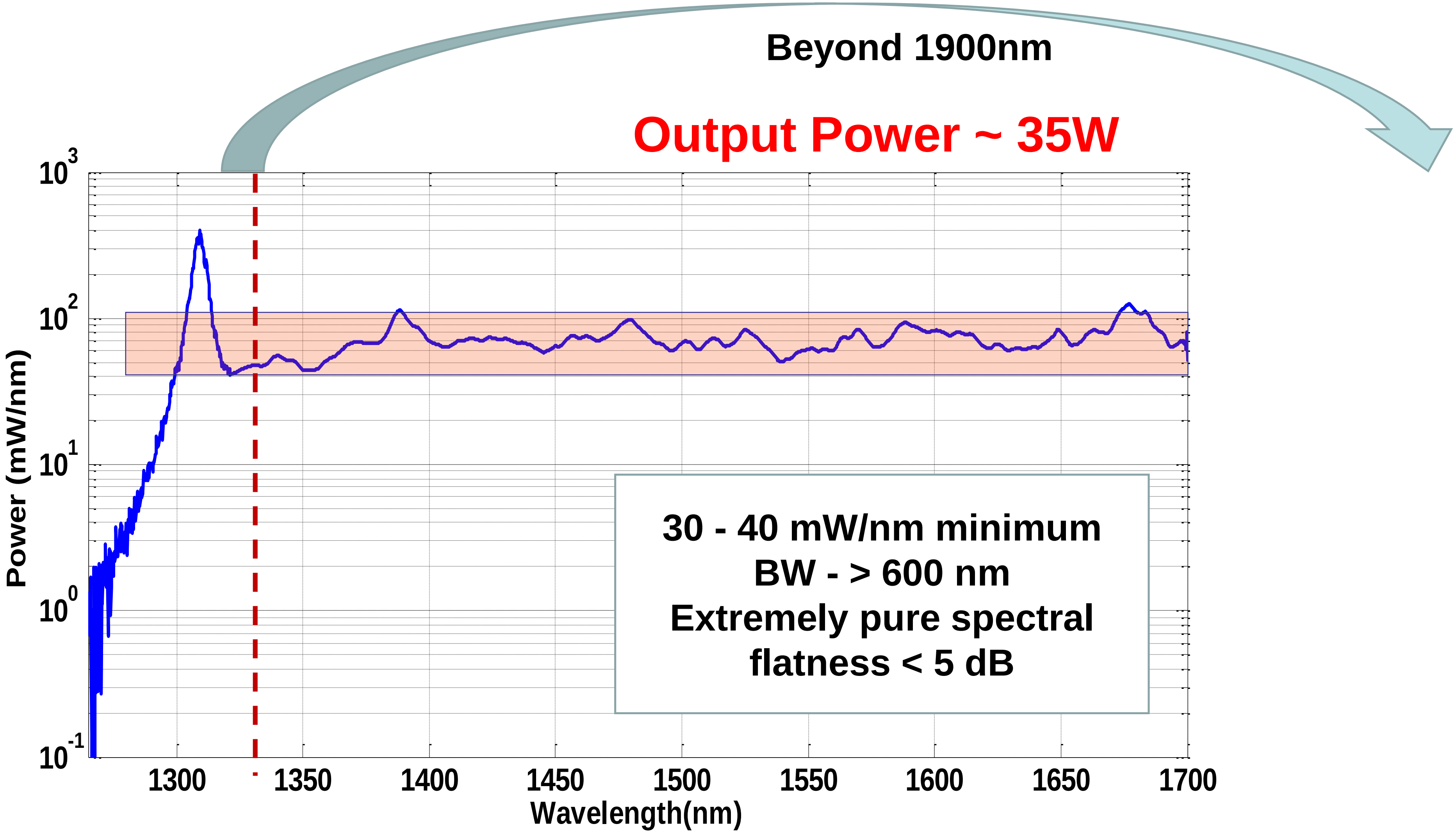
- **Zero Dispersion wavelength can be tailored for λ_0 > 1310 nm**
- **Nonlinear coefficient can also be enhanced to ~20/W-Km**
- **At 1.5 μm – closely tied up with the telecom field**



To induce Modulation Instability – Pump beyond ZDWL - λ_p > 15XX nm

Problem : Lack of a single high power source in this wavelength range

Supercontinuum – Version 1

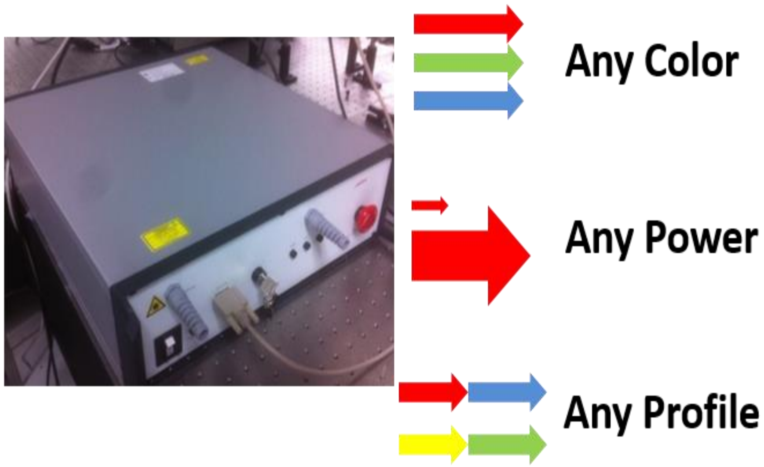


Summary

- Raman Lasers offer an excellent technology to achieve high powers scalably at a wide variety of wavelength regions.

- Our work in this field in enhancing the efficiency, reliability and system level complexity of Raman lasers was discussed.

- We also briefly looked at development of raman laser pumping, tunable lasers and supercontinuum lasers.



- The potential uses for such a source is extensive, the coming years are going to be an exciting time in Raman lasers

New review paper: V R Supradeepa, Yan Feng, Jeffrey W. Nicholson, "Raman Fiber Lasers," IOP Journal of Optics (2017)