SAND2011-3824C

Spectral Beam Compression and Combination

Sean Moore, Daniel Soh, Kevin Schroder, Wen Hsu

Sandia National Laboratories, Livermore, CA

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Statement of Problem

Directed energy community is interested in achieving >30kW continuous wave as efficiently and simply as possible

- Spectral beam combination offers simple, robust architecture for power scaling
- ~3kW Yb-doped fiber lasers with diffraction-limited output have been demonstrated, but large bandwidth (several nm) typically exceeds acceptable levels for spectral beam combination (SBC)
- ~1kW, narrow linewidth (0.5GHz)*, diffraction-limited fiber lasers available, but systems require active phase modulation and >30 sources needed to reach 30kW

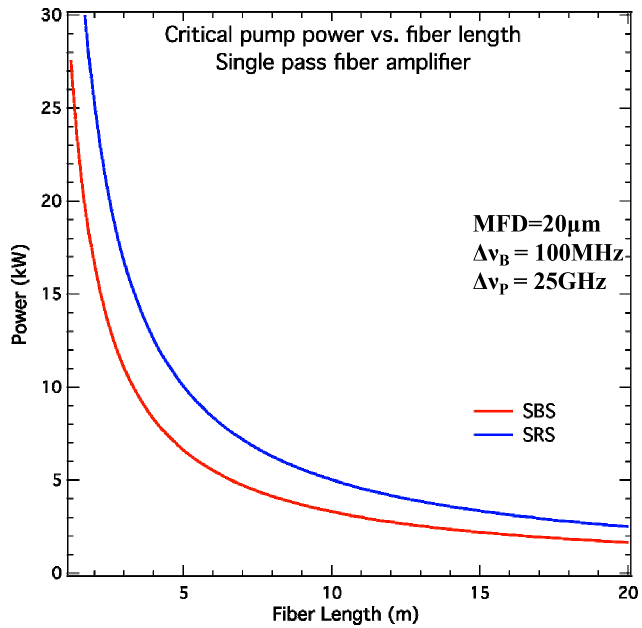
➡ ***Need multi-kilowatt, simple, narrow linewidth fiber lasers to reduce cost and complexity of SBC systems***

*D. Engin et. al., Proceedings of SPIE, Vol. 7914

Proposal for novel concept to scale to kW powers in a single fiber laser while preserving narrow (~0.1nm) bandwidth

- Use SRS in external fiber Raman cavity to Stoke's-shift and spectrally narrow output of a high power fiber laser
- Show results of model-based research conducted at multi-kW level
- Modeling and numerical simulations demonstrate that that narrow (25-30GHz, ~0.1nm) bandwidth can be achieved with use of highly dispersive fiber for Raman cavity
- Several spectrally narrowed fiber laser sources can be used for spectral beam combination (SBC)

Obstacles to power scaling in fibers using narrowband sources



$$P_{Cr}^{SBS} \cong \frac{21 A_{Eff}}{g_B L_{Eff}}$$

$$g_B = \frac{\Delta\nu_B}{\Delta\nu_B + \Delta\nu_P} \times g_B^0$$

- Achievable power from single fiber laser limited primarily by Stimulated Brillouin scattering (SBS)
- P_{Cr} for SBS can be substantially increased by increasing the bandwidth of the signal and mode field diameter to where P_{SBS}~P_{SRS}
- Introducing thermal gradients and/or strain to fiber, controlling overlap of optical and acoustic modes, phase modulation of signal can increase SBS threshold by factor ~ 4

≈ 25-30GHz (≤0.1nm) optimal bandwidth: Acceptable for Spectral Beam Combination (SBC) and broad enough to suppress SBS in fibers

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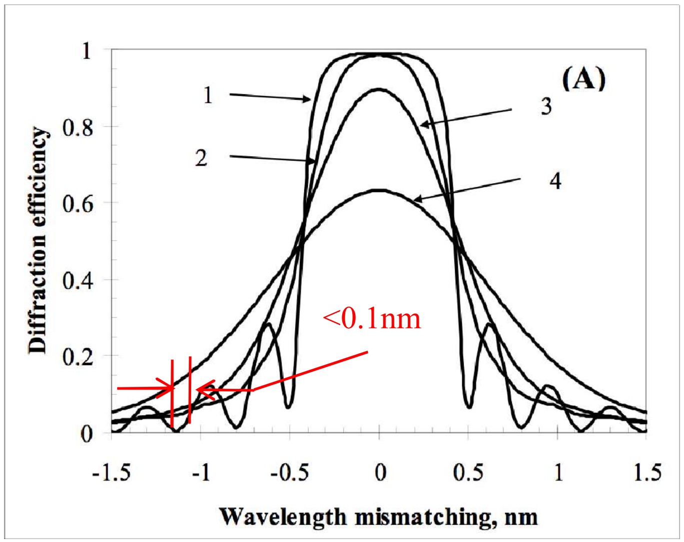
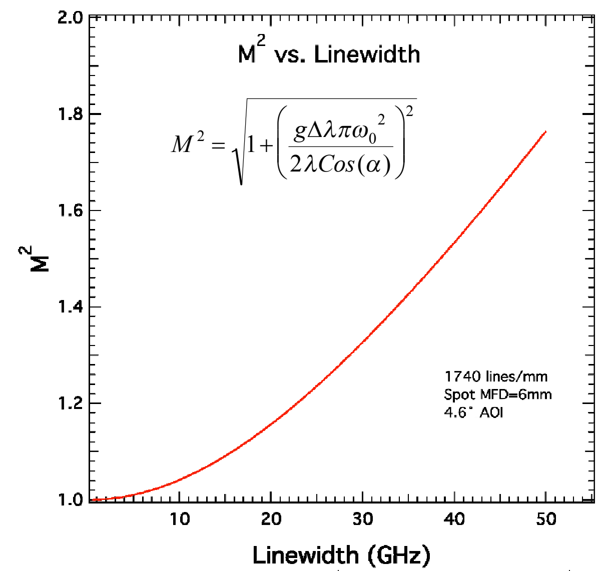
Obstacles to SBC at high powers using fiber lasers

Volume Bragg grating



From I. V. Ciapurin et. al., Proc. of SPIE Vol. 5742, pgs 183-194

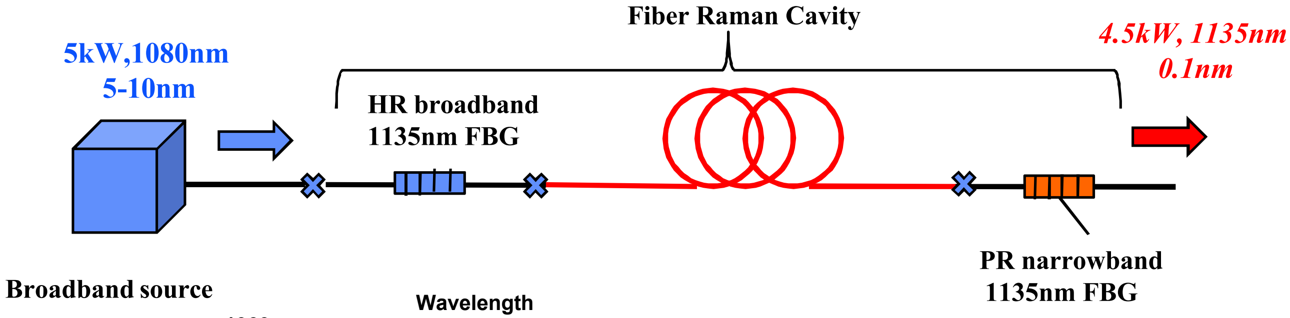
Surface Bragg grating

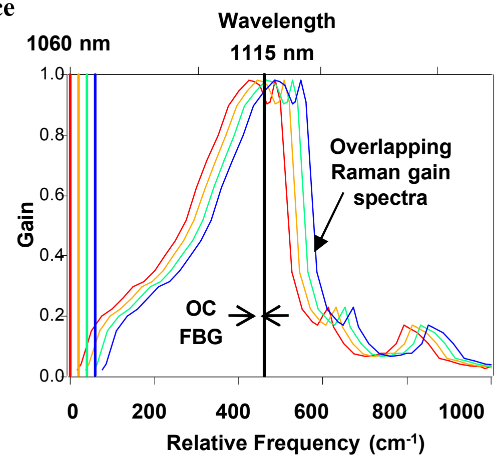


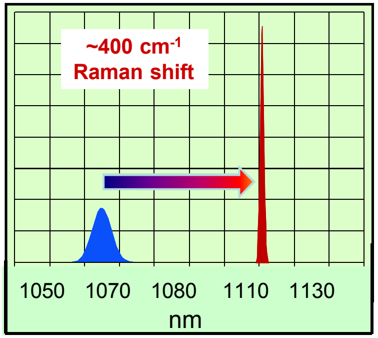
- Spectral broadening due non-linear processes (4-wave mixing, SPS, XPM) in multi-kW fiber lasers is the principle obstacle to SBC
- Spectral broadening degrades M^2 (surface grating) and overlap with diffraction efficiency nulls of adjacent channels (VBG) in SBC architecture
- Need to limit bandwidth of Yb-fiber lasers to ~0.1nm (~30GHz)

Non-linear processes in fiber lasers must be suppressed at kW level to implement SBC with good beam quality/diffraction efficiency

New Approach: Use external fiber Raman cavity to Stokes-shift broadband power to narrowband power

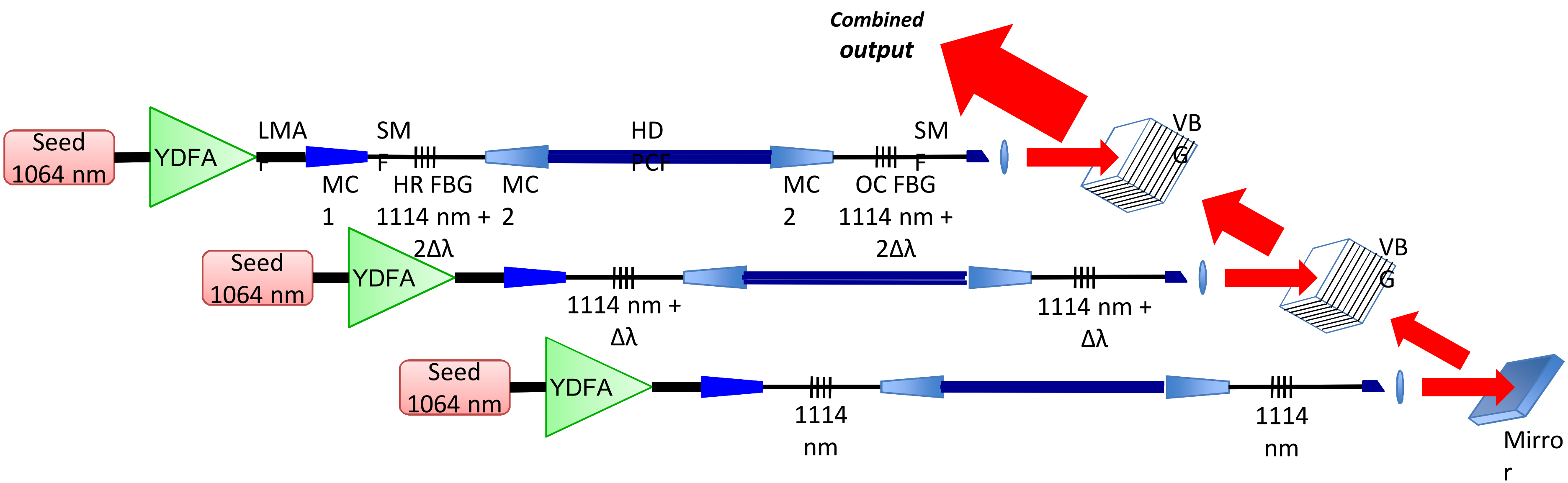






- ➢ High power, broadband pump sources (5-10nm) spectrally compressed to ≈ 0.1nm via SRS and proper selection of fiber Bragg grating bandwidths
- ➢ Large bandwidth (~8THz) of SRS in silica permits spectral narrowing of broadband (5-10nm) sources over large bandwidth
- ➢ Raman conversion in cavity is efficient (6% quantum defect)
- ➢ All fiber architecture is simple and robust

Spectra beam combination using spectrally narrowed fiber lasers



Several broadband COTS kW-class lasers can be spectrally compressed at different wavelengths via proper selection of fiber Bragg gratings and combined using SBC

Model and numerical simulator development

$$\frac{dP_i^{\pm}}{dz} = \pm \left[\begin{array}{l} -(\alpha_{mat} + \alpha_{RS})P_i^{\pm} - \alpha_{RS} F P_i^{\pm} \\ \sum_{k<i} c_{R,(k,i)} \left(P_k^+ + P_k^-\right)\left(P_i^{\pm} + h\nu_i \Delta\nu_{spon}\right) - \sum_{j>i} \frac{\nu_i}{\nu_j} c_{R,(i,j)} \left(P_j^+ + P_j^- + h\nu_j \Delta\nu_{spon}\right) P_i^{\pm} \\ -g_B P_i^{\pm} P_{i-}^{\mp} - g_B P_i^{\pm} h\nu_i \Delta\nu_{spon} \\ -\frac{2n_2'\omega_i}{c} \left\{ \begin{array}{l} 2\sum_{l\neq i}\sum_{m\neq i}\sum_{j\neq i} f_{lmji} \sqrt{P_l^{\pm} P_m^{\pm} P_j^{\pm} P_i^{\pm}} \sin\left(\Phi_{lmji}\right) \\ + \sum_{l\neq i}\sum_{j\neq i} f_{ljji} P_j^{\pm} \sqrt{P_l^{\pm} P_i^{\pm}} \sin\left(\Phi_{ljji}\right) + 2\sum_{l\neq i}\sum_{m\neq i} f_{liim} P_i^{\pm} \sqrt{P_l^{\pm} P_m^{\pm}} \sin\left(\Phi_{liim}\right) \end{array} \right\} \end{array} \right]$$

Material absorption & Rayleigh scattering

Stimulated Raman scattering

Stimulated Brillouin scattering

Four-wave mixing

Self/Cross-phase modulation

- Developed comprehensive numerical simulator for a Raman fiber laser which accounts for all non-linear processes
- Can model laser performance and spectral broadening as a function of pump laser and fiber Raman cavity parameters
- Derived analytic expression for spectral broadening ⇨

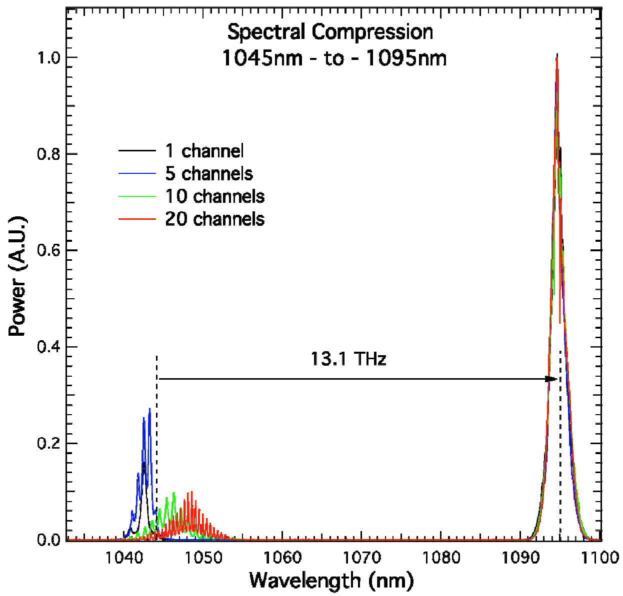
$$\frac{d\left(\rho_{peak}(z)/\rho_{peak}(0)\right)}{dz} \leq 16\gamma^2 P_0^2 e^{-\alpha z} \left(\frac{1-e^{-\alpha z}}{\alpha}\right) \mathrm{sinc}\left(\beta_2 \Omega^2 z\right),$$

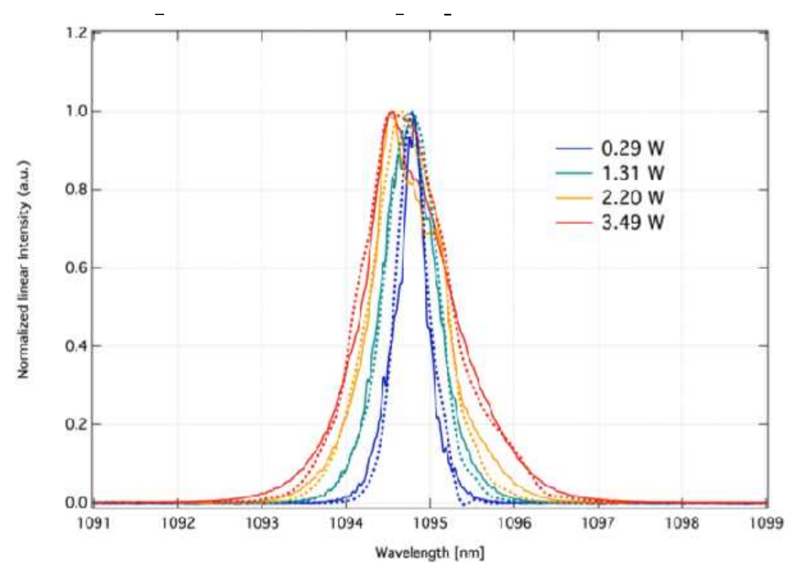
GVD

Comprehensive modeling found that very high fiber dispersion is necessary to minimize spectral broadening due to 4-wave mixing

"The effect of dispersion on spectral broadening of incoherent continuous-wave light in optical fibers", D. B. Soh, J. Koplow, S. Moore, K. Schroder, W. Hsu, Optics Express, Vol. 18, No. 21, 22393-22405 (2010)

Experimental validation of simulator at low powers

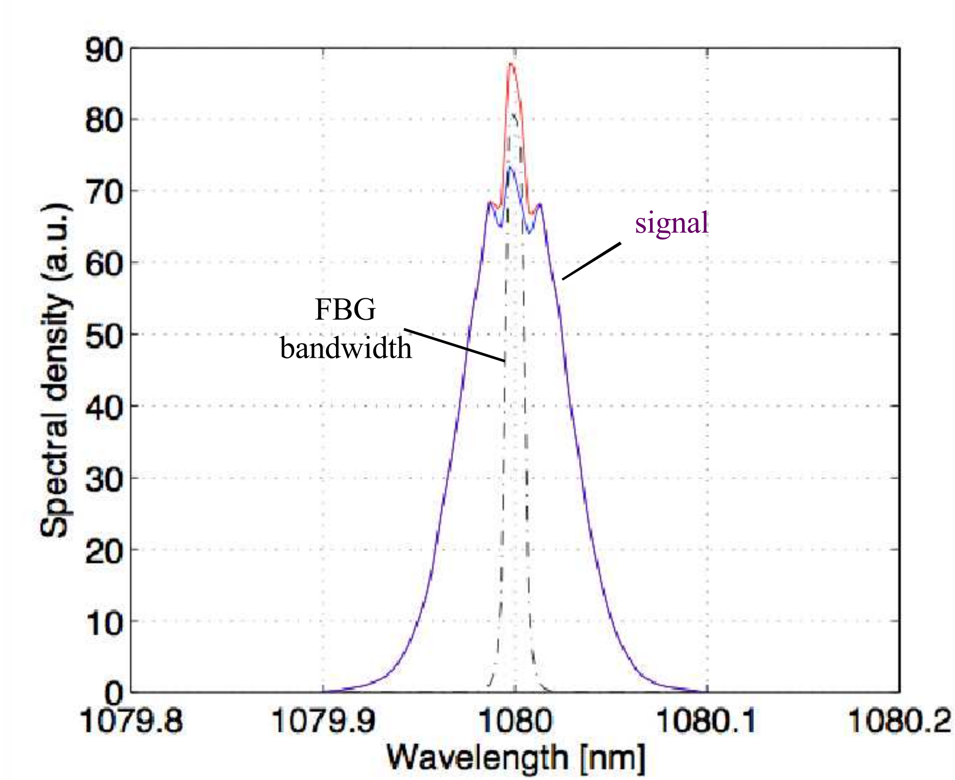




- Fiber Raman cavity = 250m HI1060 SM fiber, 5nm bandwidth HR fiber Bragg grating, 0.5nm bandwidth 20% OC fiber Bragg grating @1095nm
- Broadband amplified ASE pump centered at ≈1045nm
- 1045nm pumped spectrally compressed at 1095nm via SRS
- Spectral broadening due to 4-wave mixing observed even at low powers

Excellent agreement between numerical simulator and experiment at 5W level

Numerical simulations at 1kW



1080nm power out = 925W
Bandwidth = 0.07nm FWHM

- High dispersion fiber
  - Length: 15 m
  - Dispersion: -40 ns/nm/km
  - Mode area: 316 μm^2
- HR FBG at 1080 nm
  - Reflectivity: 99.9%
  - MFA loss: 3 % one way
- OC FBG at 1080 nm
  - Bandwidth: 0.03 nm
  - Reflectivity: 20 %
  - MFA loss: 3 % one way
- Pump : 1 kW at 1080 nm, BW >2nm

- SBS threshold = 20kW

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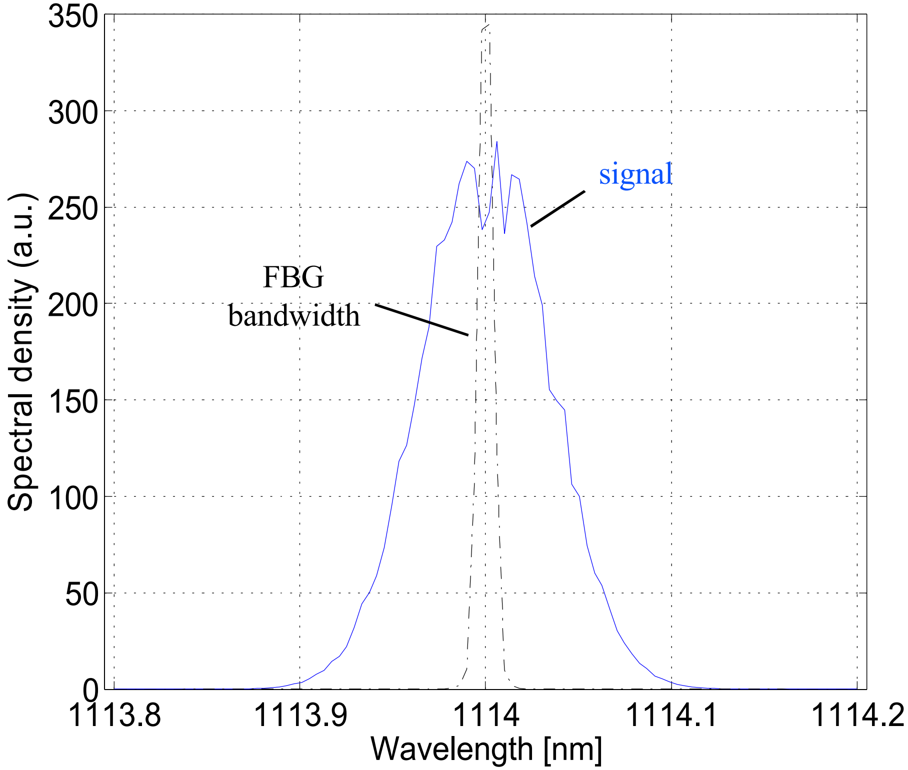
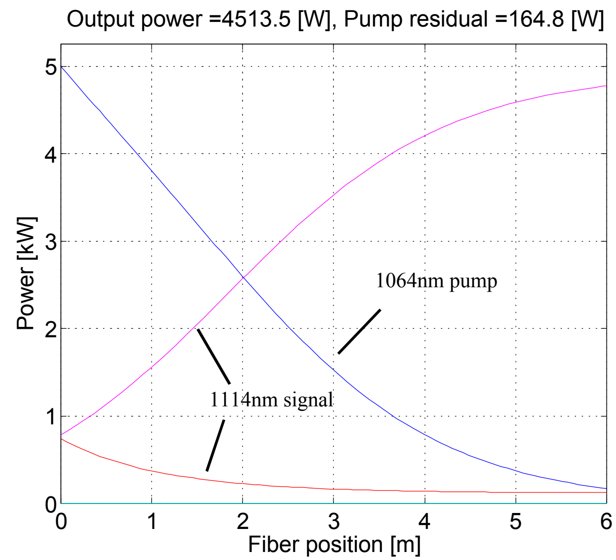
Numerical Simulations at 5kW



1114 nm output power = 4513W
Bandwidth = 0.10nm FWHM



- High dispersion fiber
  - Length: 6 m
  - Dispersion: -59 ns/nm/km
  - Mode area: 316 μm^2
- HR FBG at 1114 nm
  - Reflectivity: 99.9%
  - MFA loss: 3 % one way
- OC FBG at 1114 nm
  - Bandwidth: 0.01 nm
  - Reflectivity: 20 %
  - MFA loss: 3 % one way
- Pump : 5 kW at 1064 nm, >2nm BW

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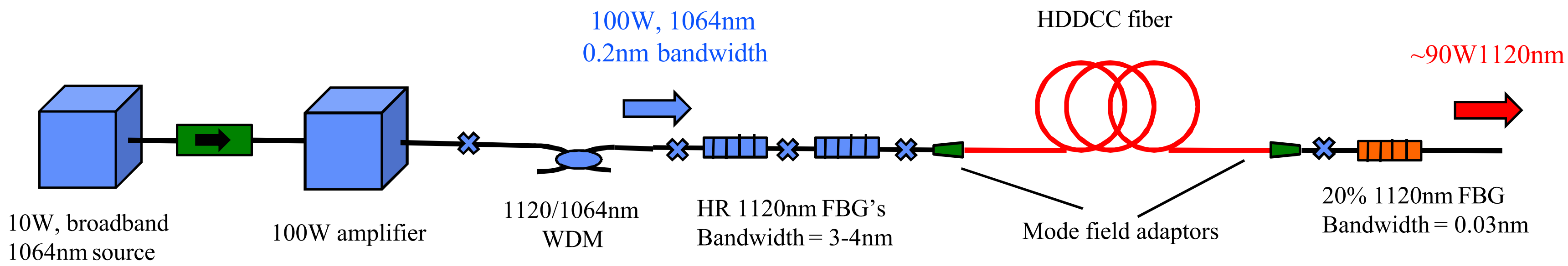
Next Step: Spectral compression at 100W level

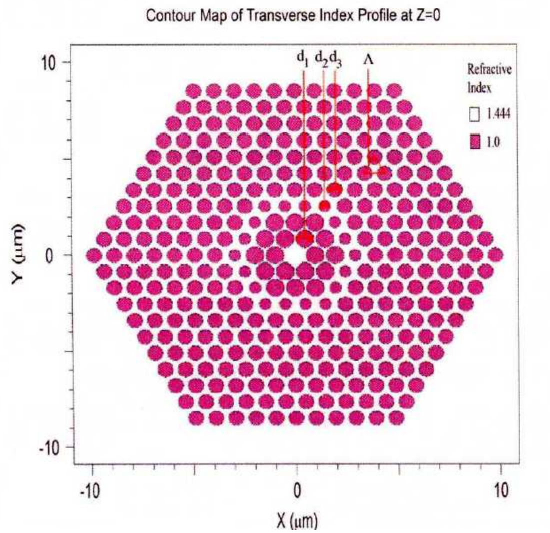


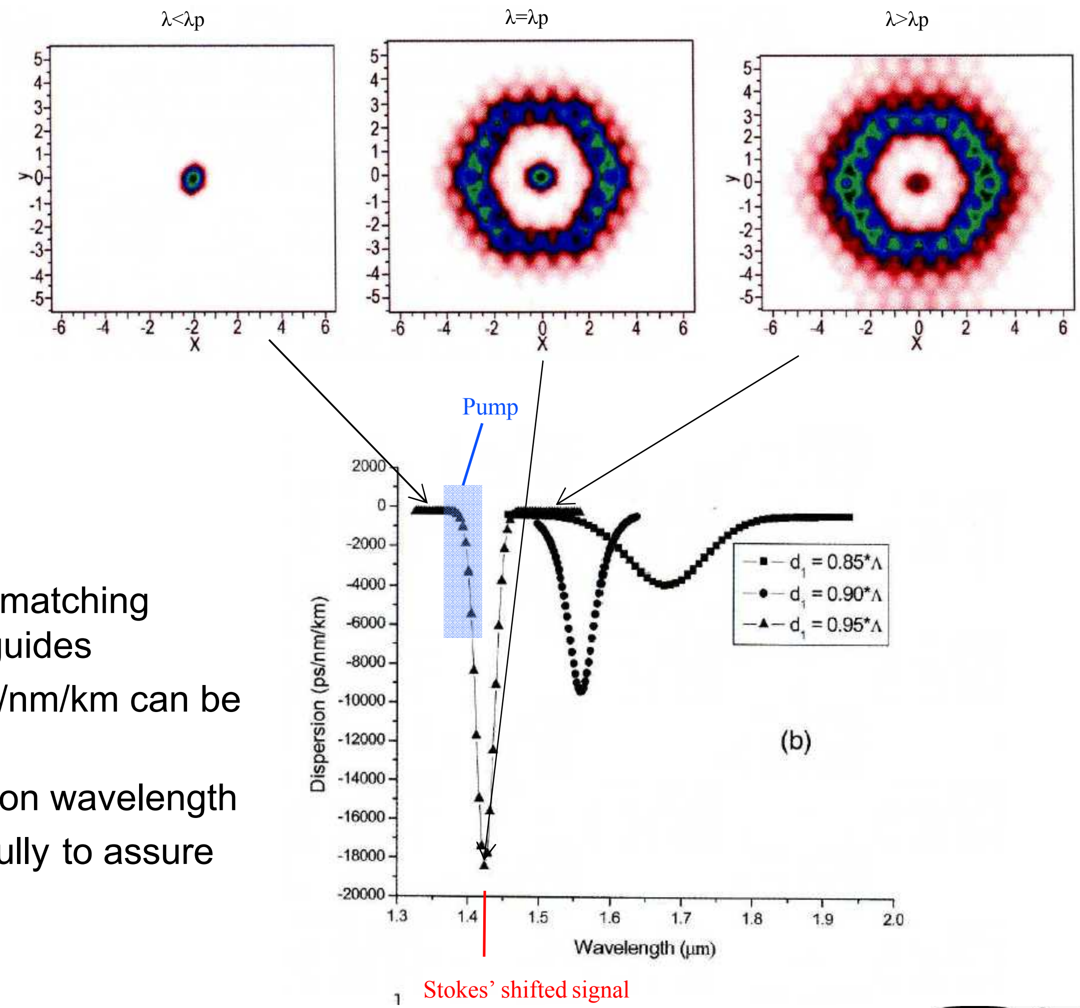
- Demonstrate spectral compression via SRS in external Raman cavity at 100W level
- 100W experiment using highly dispersive dual concentric core fiber under construction
- Results coming October 2011

Conclusion

- Proposed technique to spectrally narrow broadband output of COTS, multi-kilowatt Yb-fiber laser via external fiber Raman cavity
- Developed numerical simulator to model Raman laser at high powers
- Numerical simulations show that spectral broadening due to 4-wave mixing in Raman cavity is the principle obstacle to spectral narrowing
- Bandwidth of Stokes'-shifted spectra can be kept to ~0.1nm even at 5kW using relatively short, highly dispersive fiber
- Narrow linewidth essential for SBC
- Technique is simple, all fiber, and low cost
- If successful, will provide path forward for SBC using multi-kW power level
- 100W spectral compression experiment under construction – results expected Fall 2011

Dual concentric core highly dispersive (DCCHD) fiber





- Maximum dispersion at the phase matching wavelength of the two concentric guides
- Dispersions in excess of 10,000ps/nm/km can be achieved
- Spatial profile of mode dependent on wavelength
- Must choose λ_{pump} and λ_{signal} carefully to assure adequate spatial overlap of modes

H. Subbaraman et. al., Applied Optics, Vol. 46, No. 16, 3263 (2007)

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