2000 nm Fiber Optical Amplifiers and Single Frequency Fiber Lasers: Technology and Applications

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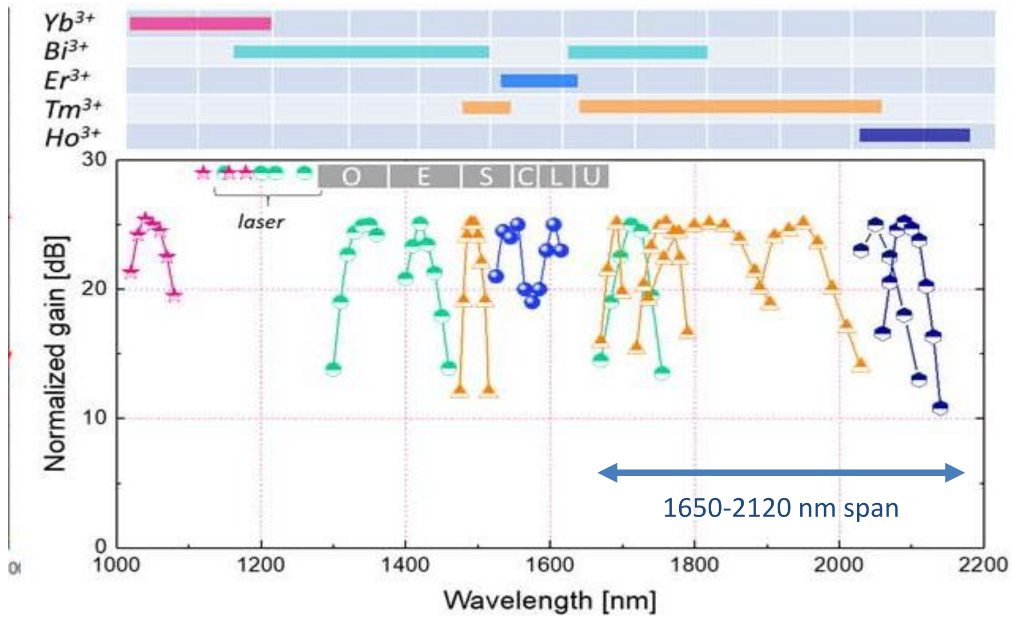
Outline

- Motivation and Objectives
- Physics and Engineering of Fiber Optical Amplifiers and Lasers
- Fiber Optical Amplifiers in the 2000 nm Band
- Single Frequency Fiber Lasers in the 2000 nm Band
- Applications to Lightwave Transmission Systems and Gravitational Wave Detection
- Potential for Wide Optical Bandwidth Lightwave Transmission Systems in the 2000 nm Band
- Applications to Future Lightwave Transmission Systems: Hollow Core NANF Fibers
- Summary and Conclusions

Motivation and Objectives: Why 2000 nm?

✓ **New Wideband Fiber Optical Amplifiers that Span More Than 300 nm Bandwidth in 2000 nm Region**

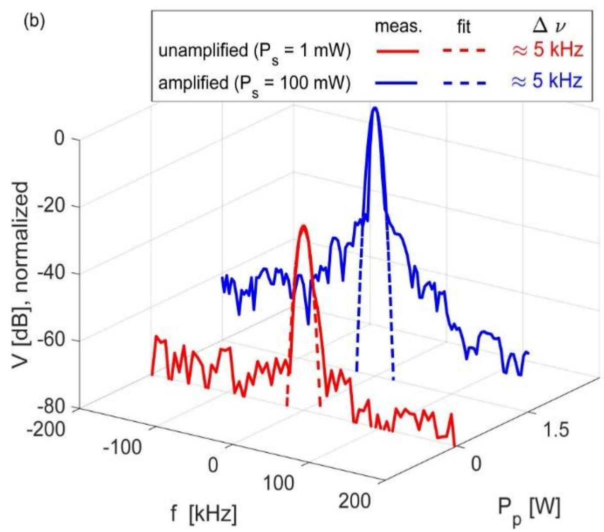


- **Thulium-doped and Holmium-doped Fiber Amplifiers are Extremely Broadband!**
- **Immediate Applications to Lightwave Systems and Gravitational Wave Detection**

D. Richardson, Tutorial W4E.1, OFC 2022

Motivation and Objectives: Why 2000 nm?

✓ **New Single Frequency Fiber Lasers that Span More Than 300 nm Bandwidth in 2000 nm Region**



- **High Power > 300 mW**
- **Extremely Narrow LW < 10 kHz**

- **Thulium-doped and Holmium-doped Fiber Lasers are Extremely Versatile!**
- **Immediate Applications to Lightwave Systems and Gravitational Wave Detection**

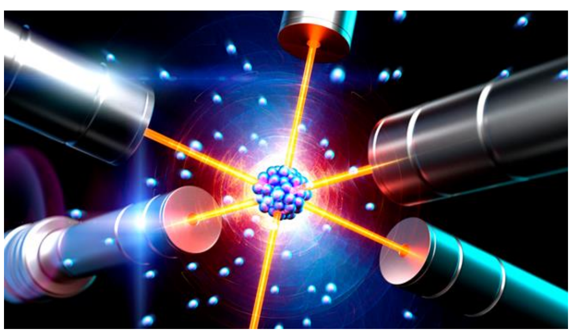
W. Walasik et al., JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 39, NO. 15, pp. 5096-5102 (2021).

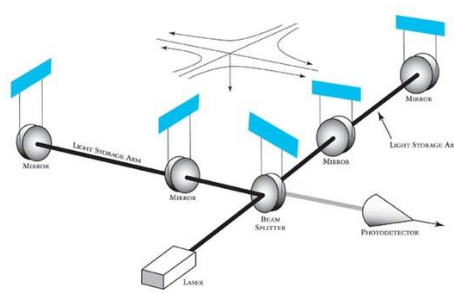
Motivation and Objectives: Some Advantages of 2000 nm Technologies

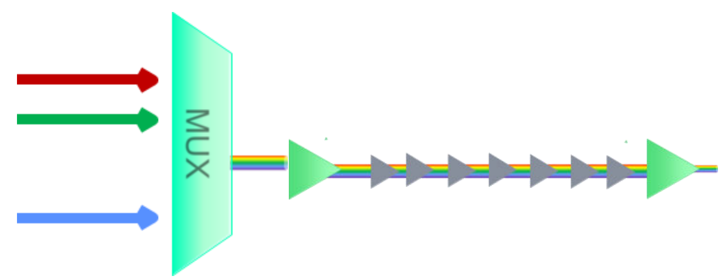
- ✓ Eye Safe Wavelengths
- ✓ Transmission through Low Loss Windows in the Atmosphere
- ✓ High Performance Manufacturable Fiber Amplifiers and Single Frequency Lasers Now Available
- ✓ Moderately Well Matched to Loss Windows of Existing Solid Core Silica Fibers
- ✓ Higher Nonlinear Thresholds in Silica Core Fibers Compared to 1064 nm and 1550 nm

Motivation and Objectives: Some Key Applications

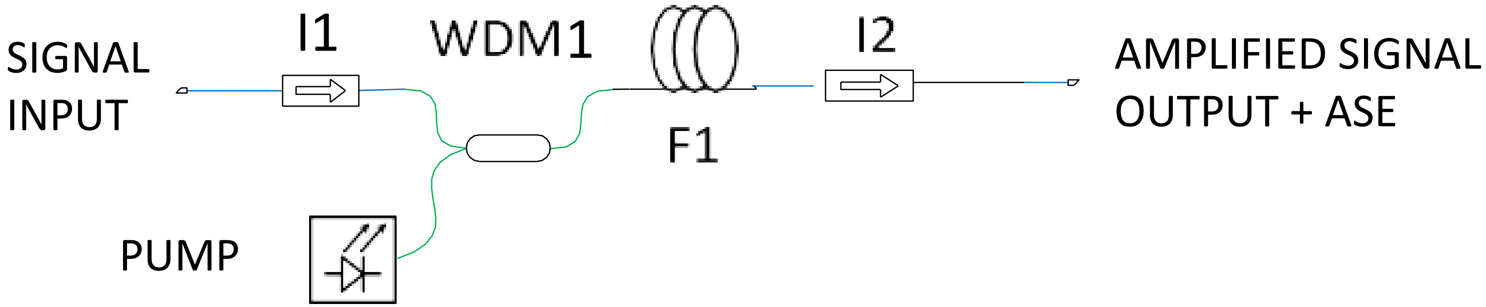
- Spectral Sensing (CO_2) at 2051 nm
- LIDAR at 2039 nm and 2051 nm
- Earth-Space Communications: 2039 nm
- Satellite-Satellite Communications: 1750-2100 nm
- Quantum Computing: Cooling of Ba Atoms at 1970 nm
- Gravitational Wave Detection by Interferometry at 2050 nm
- DWDM Lightwave Transmission Systems from 1700-2100 nm







Physics and Engineering of Fiber Optical Amplifiers: I



- **Pump Light at Lower Wavelength Generates Gain via Stimulated Emission at Higher Wavelength in Rare-Earth Doped Fiber F1**
- **Typical Input Signal Wavelengths: 1550 nm (Erbium), 1750-2100 nm (Thulium/Holmium)**
- **Typical Pump Wavelengths: 980 nm (Erbium), 793 nm and 1565 nm (Thulium), 1860 nm (Holmium)**
- **Isolators Insure Unidirectional Operation**
- **WDM1 Combines Pump and Signal With Low Loss**
- **Typical Small Signal Gains: 20-40 dB**
- **Typical Amplified Output Signal Powers: 0.1 W –5 W**

R. E. Tench et al, IEEE Journal of Lightwave Technology Vol. 39, No. 11, pp. 3546-3552 (2021).

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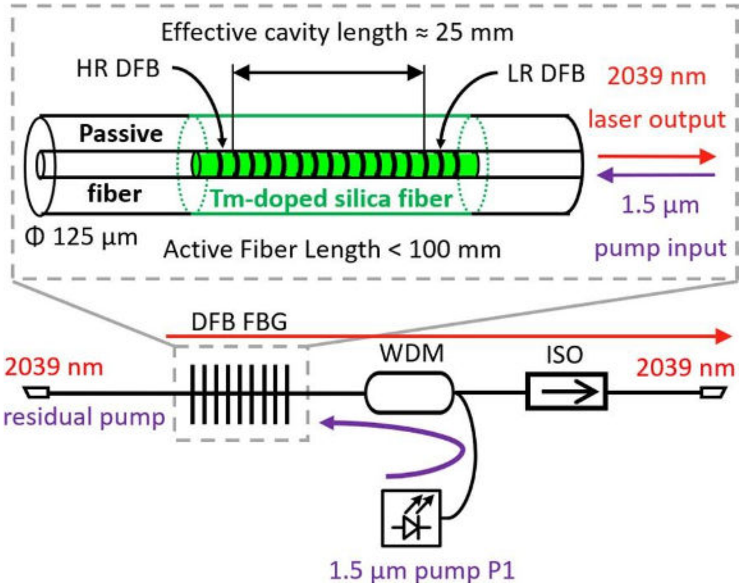
Physics and Engineering of Fiber Optical Amplifiers: II

- Two Stage Single Clad Broadband HDFA
- Pumped at 1860/1940 nm
- Over 4 W Fiber Coupled Output
- Operating BW 2000-2100 nm
- High Small Signal Gain of 59 dB
- Internal Noise Figure < 6 dB
- Package 200 x 150 x 43 mm^3
- USB and RS232 Interfaces
- 18-32 VDC Power Supply

https://www.cybel-llc.com

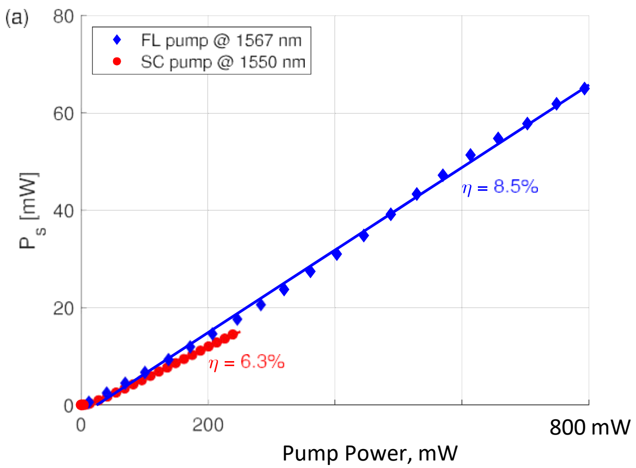
Physics and Engineering of Fiber Lasers:
Single Frequency DFB-FBG Fiber Laser Architecture



- **Pump Light at Lower Wavelength Generates Gain at Higher Wavelength in Rare-Earth Doped Fiber (Example Shows a Tm-doped Silica Fiber)**
- **Reflection Gratings at the Desired Signal Wavelength Provide Feedback that Leads to Lasing in the Gain Fiber**

W. Walasik et al., JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 39, NO. 15, pp. 5096-5102 (2021).

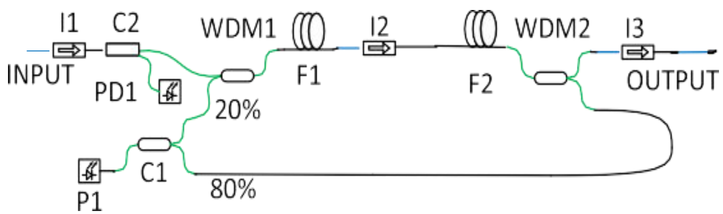
Physics and Engineering of Single Frequency Fiber Lasers: Packaging for Thermal and Environmental Stability

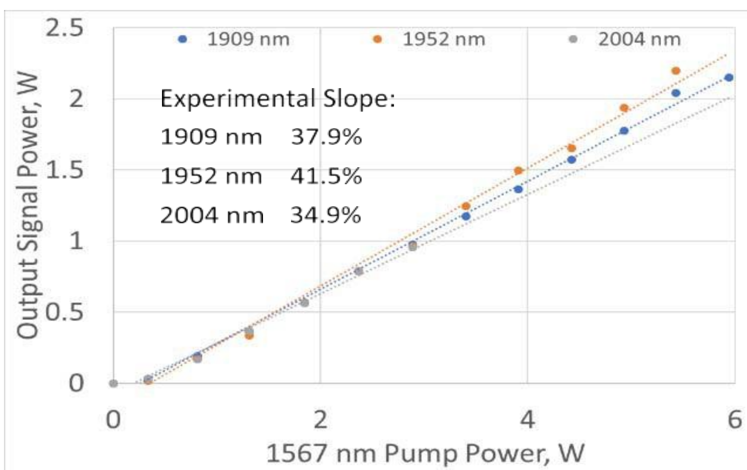


- Reflection Gratings and Tm-doped Gain Fiber Enclosed in a Custom Thermal Package for Environmental Stability
- Typical Signal Wavelengths: 1750-2100 nm (Thulium/Holmium)
- Typical Pump Wavelengths: 1565 nm (Thulium), 1860 nm (Holmium)
- Both Fiber Laser and Semiconductor Pump Laser Sources Can be Employed
- Typical Single Frequency Laser Output Power: 20-350 mW

W. Walasik et al., JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 39, NO. 15, pp. 5096-5102 (2021).

Broadband Tm-doped Fiber Amplifier: 1875-2000 nm





- **Two Stage Single Clad Broadband TDFA**
- **<u>Operating BW 1875-2000 nm</u>**
- **Pumped at 1567 nm**
- **Over 2 W Fiber Coupled Output**
- **High Small Signal Gain of 46 dB**
- **Internal Noise Figure < 5 dB**

R. E. Tench et al, IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 32, NO. 15, pp. 956-959 (2020)
Z. Li et al., Optics Express Vol. 21, No. 22, pp. 26450-26455 (2013).

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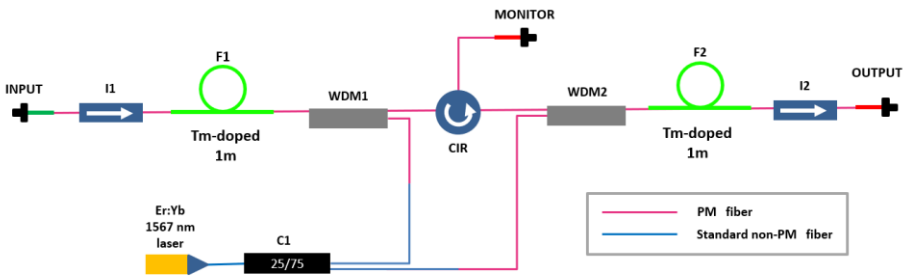
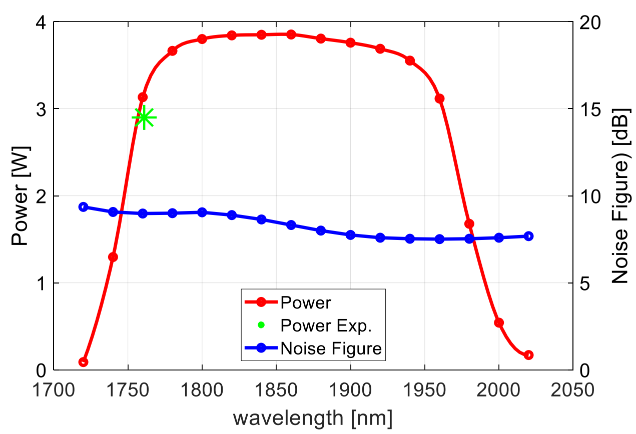
Broadband Tm-doped Fiber Amplifier: 1740-1970 nm

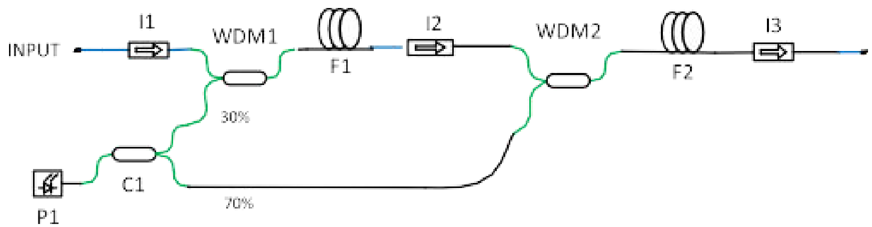


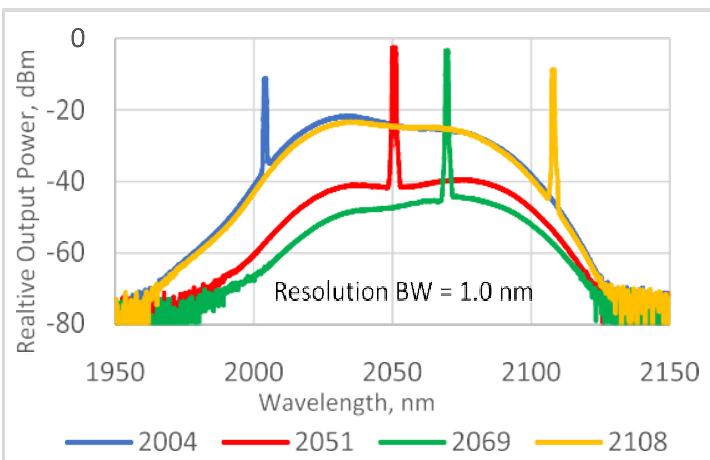


- Two Stage Single Clad Broadband TDFA, Optimized for Lower Signal Wavelengths
- Operating BW 1740-1970 nm
- Pumped at 1567 nm
- Over 3 W Fiber Coupled Output
- High Small Signal Gain of 46 dB
- Internal Noise Figure < 6 dB

W. Walasik et al., To be presented at ECOC 2022 (September 2022)
Z. Li et al., Optics Express Vol. 21, No. 22, pp. 26450-26455 (2013).

Broadband Ho-doped Fiber Amplifier: 2000-2100 nm

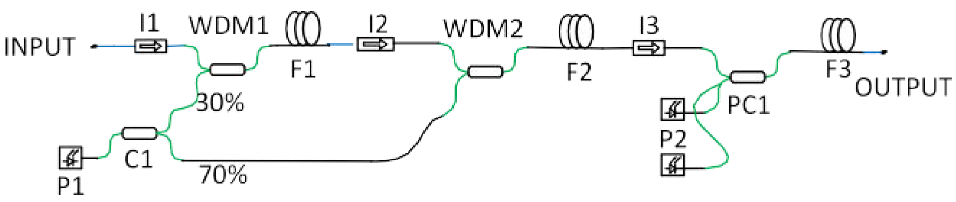


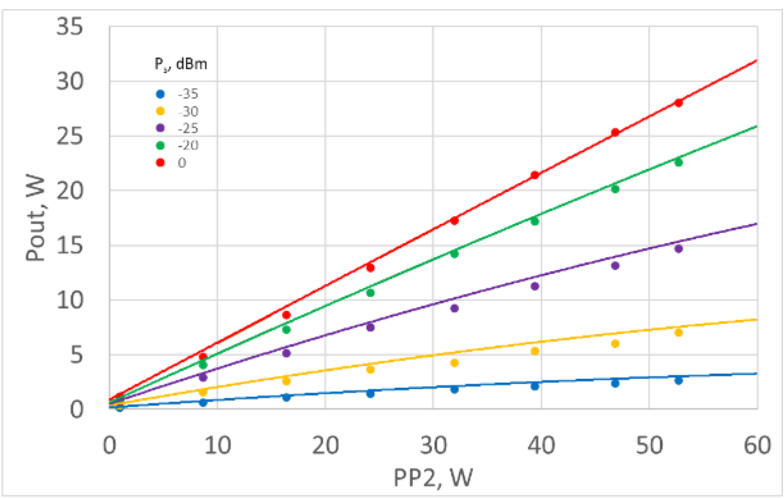


- **Two Stage Single Clad Broadband HDFA**
- **Operating BW 2000-2100 nm**
- **Pumped at 1860/1940 nm**
- **Over 4 W Fiber Coupled Output**
- **High Small Signal Gain of 59 dB**
- **Internal Noise Figure < 6 dB**

R. E. Tench et al, IEEE Photonics Technology Letters, Vol. 31, No. 5, pp. 357-360 (2019).
N. Simakov et al., OFC 2015, Paper Tu2C.6 (2015)

Hybrid Ho- and Tm-Doped Fiber Amplifier: 28 W Output Power

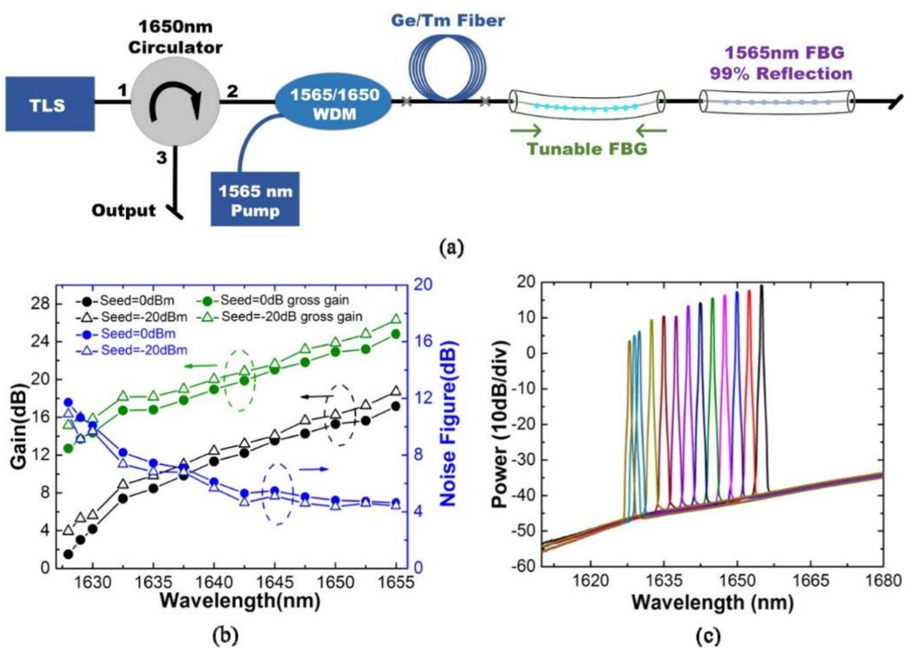




- Two Stage Single Clad HDFA Preamp Pumped at 1860/1940 nm
- Single Stage Double Clad TDFA Power Amp Pumped at 793 nm
- Over 28 W Fiber Coupled Output
- <u>Operating BW 2009-2098 nm</u>
- High Small Signal Gain of 70 dB
- Internal Noise Figure < 6 dB

R. E. Tench et al., IEEE JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 38, NO. 8, pp. 2456-2463 (2020).

High Performance Fiber Optical Amplifiers in the 2000 nm Band: Low Wavelength Tm-doped Fiber Amplifier



- Single Stage Single Clad TDFA Pumped at 1565 nm
- Specially Fabricated Ge-Tm Co-Doped Fiber
- Operating BW 1628-1655 nm
- Over 100 mW Fiber Coupled Output Power

S. Chen et al., Optics Express Vol. 27, No. 25, 36699-36707 (2019)
Z. Li et al., Optics Letters Vol. 41, No. 10, 2197-2200 (2016).

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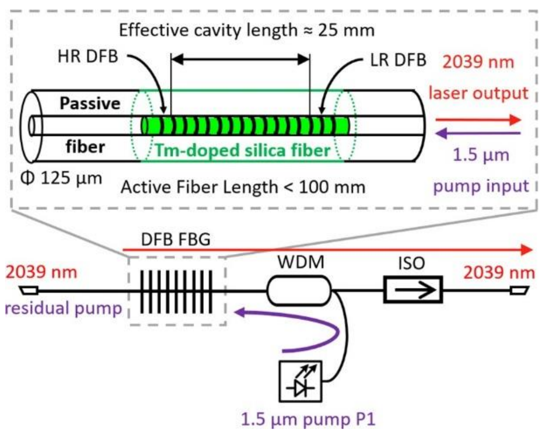
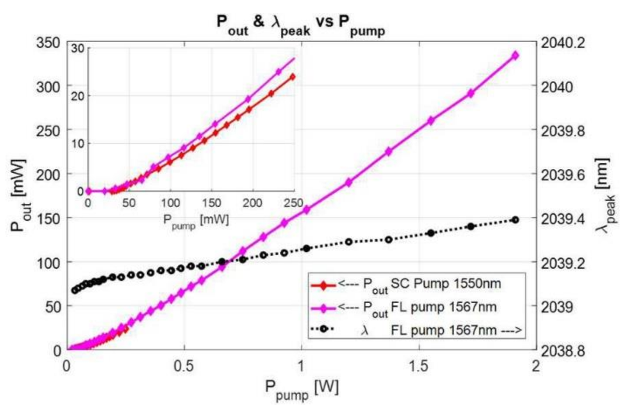
Single Frequency Fiber Laser at 2039 nm

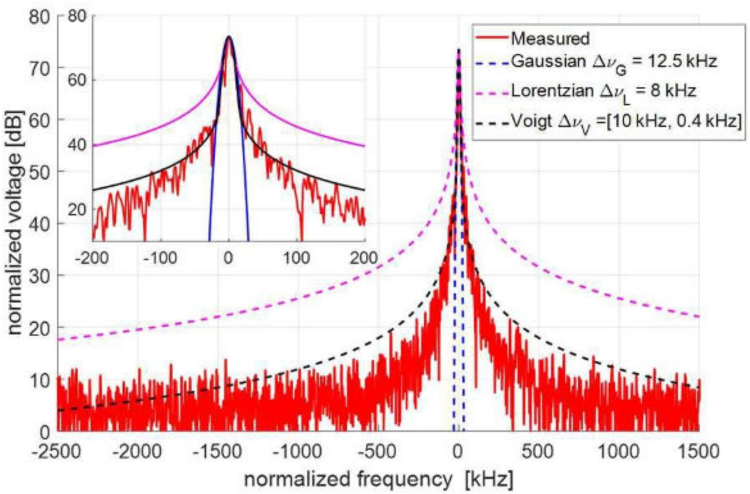




- **Single Clad PM Tm-doped FBG DFB Pumped at 1550 nm**
- **Both Semiconductor Laser Pump and Fiber Laser Pump Employed in Experiments**
- **OSNR > 65 dB**
- **Over 325 mW Fiber Coupled Output Power with Optimized Fiber Laser Design**

W. Walasik et al., To be presented at ECOC 2022 (September 2022)

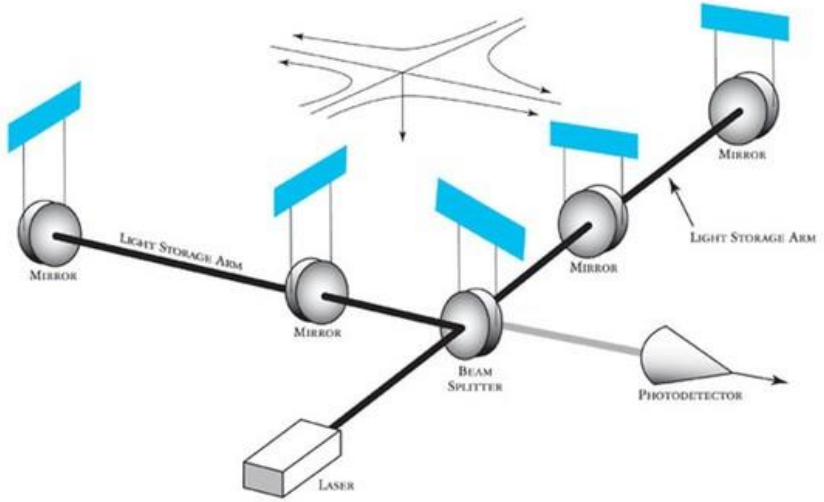
Single Frequency Fiber Laser at 2039 nm: Heterodyne Linewidth Measurement



- Single Clad PM Tm-doped 2039 nm FBG DFB Pumped at 1550 nm
- OSNR > 65 dB
- Standard Comparison Laser Source LW = 57 Hz
- Heterodyne Spectrum Fitted with Gaussian, Lorentzian, and Voigt Profiles
- Measured Heterodyne LW of FBG-DFB ~ 10 kHz
- Measurements of RIN and Phase Noise in Progress

W. Walasik et al., To be presented at ECOC 2022 (September 2022)

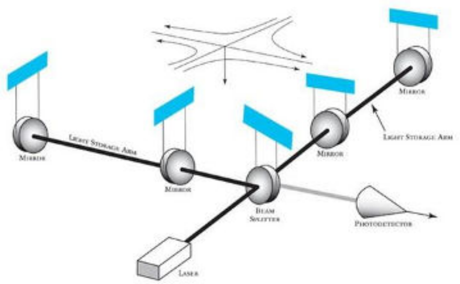
Applications to Gravitational Wave Detection: Interferometers



- Key devices: The single frequency laser source, the interferometer, the mirrors, and the high power optical amplifier used to boost the single frequency source
- The limiting detection sensitivity of the system depends on the length of the light storage arms, the linewidth of the single frequency source, the output power of the amplified laser source, and the thermal noise in the mirrors at the operating wavelength.

https://www.ligo.caltech.edu/page/what-is-interferometer

Applications to Gravitational Wave Detection: Interferometers at 2050 nm



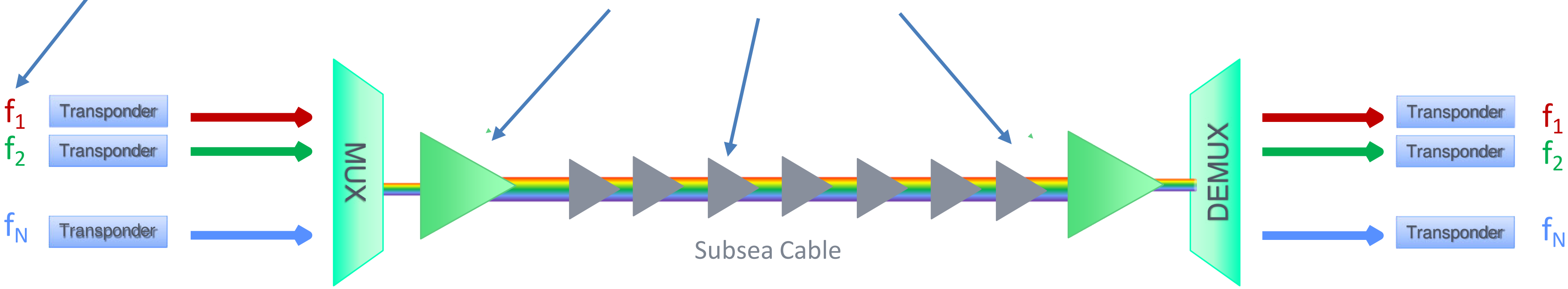
https://www.ligo.caltech.edu/page/what-is-interferometer

- Key Device: Narrow Linewidth Single Frequency Laser Source Capable of Frequency Stabilization: Realized at 2050 nm with DFB-FBG Fiber Laser
  - ✓ Using External PDH Frequency Stabilization to Reduce LW to ~ 1 Hz
- Key Device: High Power Amplifier at 2050 nm Capable of 30-50 W Output Power: Realized with Hybrid HDFA/TDFA
- Key Device: High Performance Mirrors at 2050 nm to Reduce Thermal Noise Limit: Under Research and Development

Applications to Fiber Transmission Systems: DWDM Lightwave Systems

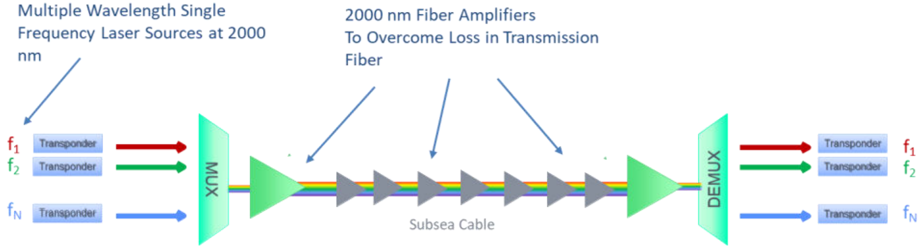
Multiple Wavelength
Single Frequency Laser
Sources

Fiber Amplifiers
To Overcome Loss in
Transmission Fiber



- Key devices: Single frequency lasers, wideband fiber optical amplifiers, and transmission fibers
- <u>The transmission capacity of the system in Tb/s depends linearly on the operating bandwidth of the fiber amplifiers and the transmission fibers</u>

Applications to Fiber Transmission Systems: DWDM Lightwave Systems at 2000 nm



- Key device: Single frequency lasers at 2000 nm: Realized with 2000 nm FBG-DFB
- Key Device: Wideband composite fiber amplifiers: Realized with > 300 nm Composite Bandwidths Possible with TDFAs and HDFAs
- Key Device: Wideband Transmission Fiber at 2000 nm: Under Research and Development

Potential for High Bandwidth Fiber Optical Transmission Systems: Comparison Matrix for 1550 nm and 2000 nm

Key Component/Device	Realized at 1550 nm	Realized at 2000 nm
Single Frequency Laser Source	**YES 70 nm BW Range**	**YES > 300 nm BW Range**
Integrated Transponder	YES	Physics-YES; Engineering-REQUIRED
Amplitude/Phase Modulator	YES	YES
High Speed Photodetector	YES	YES
Wideband Fiber Amplifiers	**YES-70 nm BW**	**YES->300 nm BW**
Wideband Transmission Fiber	**YES-80 nm BW**	**DEVELOPMENT REQUIRED: POTENTIAL for 400 nm BW**
DSP for Coherent Transponder	YES	YES

Expanded and updated from the analysis of F. Gunning et al., Applied Optics Vol. 57, No. 22, E64-E70 (2018).

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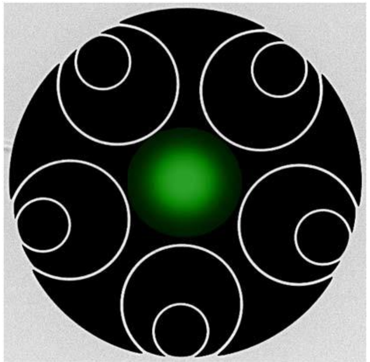
Potential for High Bandwidth Fiber Optical Systems in the 2000 nm Band: Future Transmission Fibers

HCFs for Telecommunications: NANF Hollow Core Fiber



Key Attractions

- Minimum latency (with high thermal stability)
- Ultralow nonlinearity
- Low flat dispersion (at any desired wavelength)
- Ultra-broadband transmission
- Potential for ultralow loss – below silica?
- No Rayleigh back scatter
- Radiation hard

D. Richardson, Tutorial W4E.1, OFC 2022

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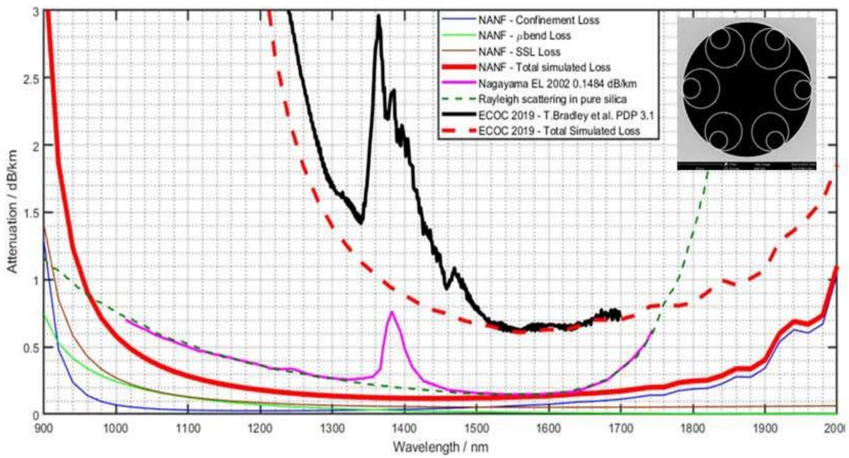
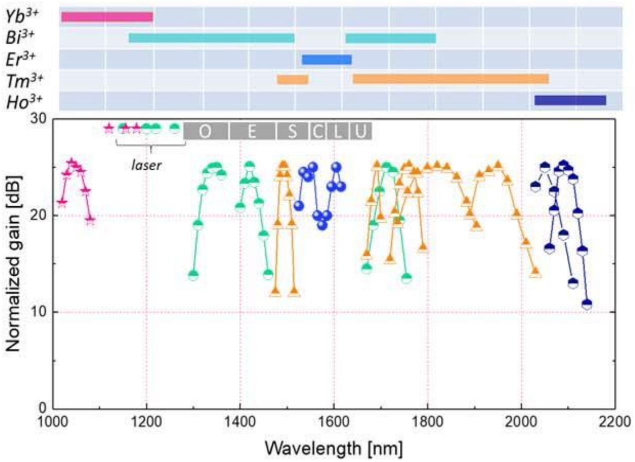
High Bandwidth Fiber Optical Systems in the 2000 nm Band: Potential for NANF Hollow Core Fiber

Plausible future HCF performance predictions



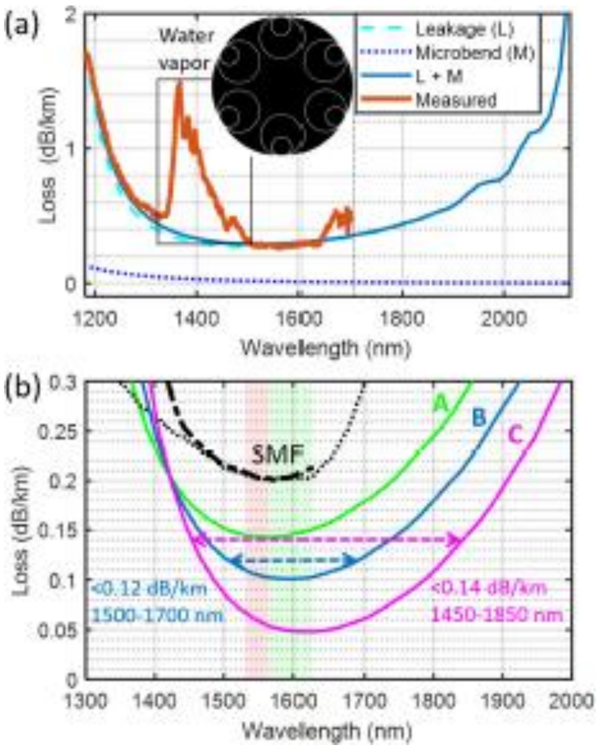
Optical fiber amplifier coverage



- **The primary loss mechanisms in HCF can be well modeled and are in excellent agreement with experiments**
- **Lower loss over wider bandwidths than SMF predicted for plausible and manufacturable designs**
- **Potential to better exploit/open up new lower loss spectral transmission windows**
- **Long-term potential for ultrawideband amplified systems using emerging silica based amplifiers**

D. Richardson, Tutorial W4E.1, OFC 2022

Potential for High Bandwidth Fiber Optical Systems in the 2000 nm Band: NANF Hollow Core Fiber



- **Theoretical Potential for Losses of < 0.14 dB/km from 1450-1850 nm (Curve C in (b))**
- **<u>New Proposed NANF Fiber Design: Shift Curve C by 300 nm Toward Higher Wavelengths</u>**
- **New Proposed Fiber Yields: > 0.14 dB/km Loss from 1750-2150 nm**
- **Ideal for > 300 nm BW TDFA and HDFA Amplification**
- **This new proposed fiber is the one missing piece to the 2000 nm DWDM transmission puzzle!**

P. Poggolini and F. Poletti, IEEE Journal of Lightwave Technology, Vol. 40, No. 6, 1605-1616 (2022).

Summary and Conclusions: Technology and Applications

- **Extremely Wide Range of Applications of Fiber Optical Amplifiers and Single Frequency Lasers in the 2000 nm Band**
- **Technology of Ho/Tm Fiber Amplifiers and Single Frequency Lasers is Fully Developed and Now In Manufacture**
- **Key Applications Include Gravitational Wave Detection and Future DWDM Lightwave Systems**

Summary and Conclusions: DWDM Systems at 2000 nm

- KEY TECHNOLOGY: Ho-doped Fiber Amplifiers and Tm-doped Fiber Amplifiers Exhibit Watt-Level Output Powers and Composite Operating BW of > 300 nm
- KEY TECHNOLOGY: Tm-doped Single Frequency Fiber Lasers Exhibit 10 kHz Linewidth and > 350 mW Output Powers in the 2000 nm Band
- Potential Dramatic Increase of 4-5 x in Transmission Capacity for Future DWDM Lightwave Systems
  - ✓ KEY TECHNOLOGY: Requires Future Development of Optimized NANF Hollow Core Fibers for 2000 nm Band, Which Is Now In Progress
- The Future for 2000 nm Band Fiber Amplifiers and Single Frequency Lasers is Bright and Promising: Come Join Our Efforts!

- **QUESTIONS?**

- **Thank You For Your Attention!**