Highly Doped Phosphate Glass Fibers for Fiber Lasers and Amplifiers with Applications

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Rare-earth doped fiber lasers and fiber amplifiers are highly attractive due to their efficiency, compactness, and, particularly, for their potential to various applications including communication systems, biomedical equipment, materials processing, LIDAR, and fiber-optic sensing. At the heart of these devices is the active fiber – most commonly based on silica host glass. However, the ability to dope silica glass fibers with high concentrations of erbium is limited due to clustering and nonlinear up-conversion – both of which degrade the efficiency of the gain fiber. Over many years, we have focused on developing highly doped phosphate glass fibers. The erbium concentrations can reach 4-5% weight erbium concentration without any negative effect to the optical gain. As a result, highly erbium doped phosphate glass fibers can produce large gain per unit length (typically 5 dB/cm) [1, 2]. This characteristic is a key enabler for a variety of optical devices that can make use of high optical gain in a short length – most notably high power single frequency fiber lasers and short length fiber amplifiers. In this presentation, we focus on two applications of the highly doped phosphate fiber. One is a high power, narrow linewidth single frequency fiber laser. The second is a fiber amplifier for coherent LIDAR applications capable of power scaling transform limited pulses without deleterious nonlinear effects. Both are examples of how this type of active fiber can lead to unique and superior performance.

Single Frequency Fiber Laser

The laser structure consists of a short length (2 cm) of heavily Er:Yb co-doped phosphate glass fiber placed inside a linear cavity made from fiber bragg grating reflectors written in silica fibers.[3] This basic all-fiber structure is energized with a telecommunications-grade Bragg grating stabilized semiconductor laser operating at 975nm. The fiber laser produces single-frequency output power (> 150 mW) at C-band wavelengths (1530nm-1565nm) with narrow linewidth (1-3 kHz), low relative intensity noise (RIN) and low phase noise. In addition to thermal wavelength tuning, the laser frequency can be modulated via a piezoelectric actuator. The laser has a linearly polarized output, and low sensitivity to external vibrations and acoustic noise. Recently, we have developed a new Er:Yb co-doped phosphate glass fiber with Er doping concentration optimized for low noise operation which significantly improves the laser noise performance while still maintaining high output power (> 100 mW) directly from the oscillator operating at 1550nm. We introduce some of those results in the following. For many applications, particularly for interferometric fiber optic sensing, low phase noise lasers are essential. In addition, the low frequency part of the spectrum (<1 kHz) is especially important in seismic oil and gas sensing. Figure 1 shows the phase noise of a recently fabricated fiber laser. The low frequency phase noise performance is superior to the solid state NPRO laser. Not only does this fiber laser offer a new level of sensitivity and resolution for fiber-optic sensing systems, it provides it in a much more compact and cost effective form.

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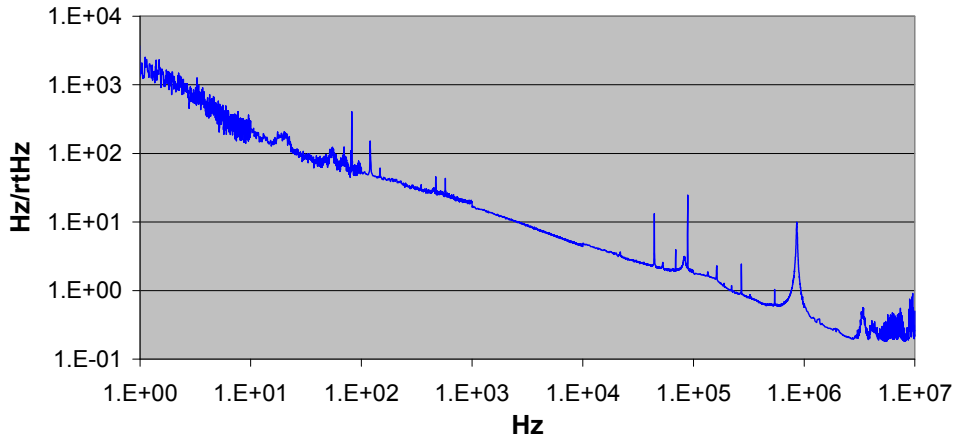

Figure 1. Phase Noise Spectrum of the NP Photonics Fiber Laser

The phase noise spectrum offers a complete description of the laser noise. However, often the linewidth of the laser is used to quantify the spectral purity. Figure 2 shows the linewidth of the laser as measured by the 25km self heterodyne setup used. In this measurement, the spectral width 20dB down from the peak is 10.47 kHz – which, if we assume a Lorentzian line shape, corresponds to linewidth of ~500Hz. This plot shows interference artifacts at the wings produced by the limited length of fiber in the interferometer, but this is indicative of a linewidth that is narrower than 500Hz.

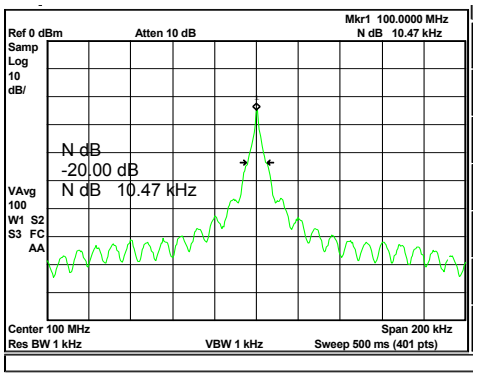

Fig. 2. Heterodyne linewidth measurement

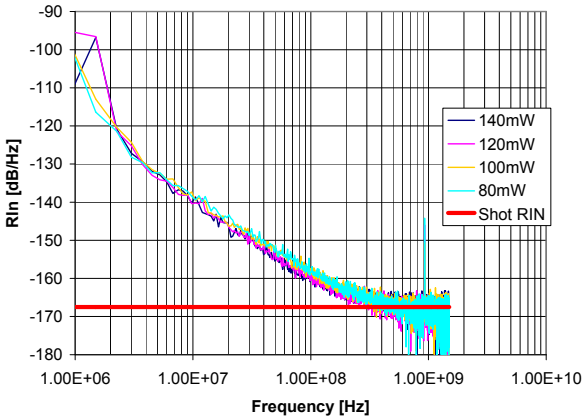

Fig. 3. Relative Intensity Noise Spectrum

This same laser has exceptional high frequency RIN performance. Figure 3 shows the RIN spectrum for various output powers directly from the fiber laser oscillator. With this detection system, we reach a shot noise limited performance of ~ -170dB/Hz. This low noise performance at high frequencies is ideal for RF photonics where low RIN noise and high power are required.

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Coherent LIDAR applications based on large core highly doped phosphate fibers

Coherent LIDAR can benefit greatly from fiber laser transmitters with high power and narrow linewidth pulses [4-5]. For these applications, high precision measurements depend on the linewidth or coherence length of the fiber laser pulses. Therefore, the fiber laser pulses should have large enough pulse duration to take full advantage of the narrow linewidth in a transform-limited pulse. In longer nanosecond pulses that are both single spatial mode and very narrow linewidth, laser power or pulse energy scaling in fiber amplifiers has been difficult due to optical nonlinearities, primarily from stimulated Brillouin scattering (SBS). In pursuing the high SBS-threshold for pulsed fiber laser and amplifier, we use the large core highly co-doped phosphate fibers (LC-EYPhF) with single-mode (SM) performance and high unit gain. Fig. 4 shows pictures of two large core highly Er/Yb co-doped phosphate fibers we have developed recently. One has a core diameter of 15 μm, which can generate 54 μJ pulse energy and 332 W peak power for 153-ns pulses with transform-limited linewidth at 1538 nm [4]. Here, we report more than kilowatt SBS-threshold for transform-limited longer ns pulses based on a new LC-EYPhF fiber 25/400, whose core and cladding sizes are 25 μm and 400 μm, respectively. This large core fiber has core doping concentrations of 3wt% Er and 15wt% Yb, core numerical aperture (NA) of ~ 0.0395, and a V-number of ~ 2. This low NA large core fiber has been fabricated based on a rod-in-tube technique under precise refractive index control for core and cladding glasses.

Fig. 4 Pictures of two large core highly Er/Yb co-doped phosphate fibers.

Fig. 5 shows the monolithic pulsed fiber laser system based on a MOPA architecture. The fiber laser consists of a single-frequency Q-switched fiber laser seed that we have developed recently [4], two pre-amplifier stages using commercial active fibers, and two power amplifier stages using the LC-EYPhF fibers 15/125 and 25/400. From Fig. 5, one can see that the fiber lengths for two large core fibers are very short - 12.5 cm and 15 cm, which have been theoretically and experimentally optimized. Most importantly, the whole fiber laser is a monolithic fiber system based on MOPA configuration.

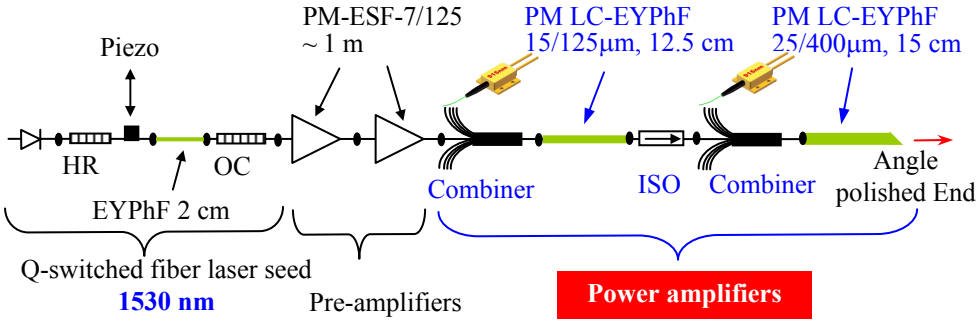

Fig. 5 Schematic of narrow linewidth pulsed monolithic fiber laser: HR, high reflective fiber Bragg grating; OC, Fiber Bragg grating output coupler; ISO, isolator.

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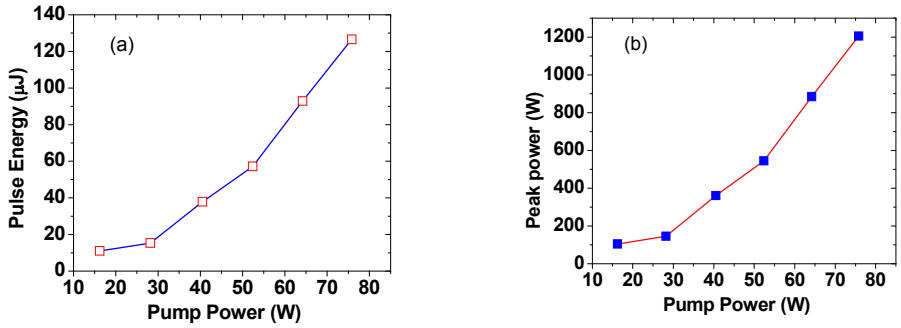

Fig. 6 (a) Output pulse energy and (b) Output peak power of the 2nd power fiber amplifier at different pump power at 975 nm when the repetition rate is 8 kHz.

Fig. 6 (a) shows the output pulse energy with SBS-free at different pump powers at 975 nm for the 2nd power amplifier stage when the input pulse duration is 112 ns at 1530 nm with repetition rate of 8 kHz. The highest pulse energy can reach 0.126 mJ without SBS. The amplified pulse width is about 105 ns which is slightly narrower than the seed pulse width of 112 ns, and the pulse shape is still Gaussian-like. From Fig. 6 (b), it is worth noting that the highest peak power can reach 1.2 kW for 105 ns pulses with a repetition rate of 8 kHz. The amplified SM pulses have a signal-to-noise ratio of ~ 50 dB. The measured M^2 value is in the range of 1.2-1.4 for different final output pulse energy levels. The transform-limited linewidth for the amplified fiber pulses was verified by using a scanning Fabry-Perot interferometer [4, 6]. This monolithic pulsed fiber laser transmitter can be used for coherent LIDAR and active remote sensing.

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