Phosphosilicate Raman Gain Fibers with Varying Core Concentration for Enhanced SBS Suppression

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***Abstract*— New SBS suppressed phosphosilicate Raman gain fibers are demonstrated with longitudinally varying core doping concentrations. Peak Brillouin gain is reduced by 6 dB over standard fibers resulting in a 2.8 dB increase in amplified power.**

***Index Terms*—Fiber Optics, stimulated Raman scattering, stimulated Brillouin scattering, optical fiber amplifiers.**

I. Introduction

Fiber lasers and amplifiers are rapidly being deployed for remote sensing and LIDAR applications due to their compactness and robust design as compared to conventional laser sources [1]. In particular, high-power, narrow-linewidth fiber lasers are needed for performing spectroscopic measurements [2]. But while such sources using rare-earth doped fibers are commercially available in the 1.06 µm, 1.55 µm, and 2.0 µm spectral bands, fiber lasers tuned to spectroscopic features of interest at other wavelengths are much less mature. Developing amplifiers and lasers based on stimulated Raman scattering (SRS) in optical fiber is one potential method for overcoming the spectral limitations of current fiber laser technology [3].

In contrast to rare-earth doped fibers, the optical gain provided by Raman fibers is much lower, thereby necessitating the use of much longer gain fibers in Raman amplifiers and lasers. With this increased gain fiber length though, the effects of stimulated Brillouin scattering (SBS) become more pronounced, severely limiting the total output power that can be realized from such devices. In this paper we present for the first time the development of new phosphosilicate Raman gain fibers with relatively low attenuation and longitudinally varying core doping concentration levels exceeding 9 mol% over lengths on the order of hundreds of meters that provide for both high Raman gain and enhanced SBS suppression, offering the potential for watt-level amplification of narrow linewidth seed sources across most of the near-infrared spectral band. These fibers stand in contrast to previous efforts in germanosilicate which either resulted in high loss short fibers [4], prohibitive to Raman amplification, or fibers with lengths in excess of several kilometers which significantly decrease the Brillouin threshold under high-power amplification [5-6].

II. Varying Concentration Phosphosilicate Fibers

Compared to other common silicate glass dopants such as GeO_2 and B_2O_3, phosphosilicate (P_2O_5-doped) fibers are attractive for use in Raman amplifiers due to their unique Raman shift at approximately 1330 cm^{-1} [7]. When pumped by commercial fiber laser technology (e.g. Yb^{3+}, Er^{3+}, etc.), the nearly three times larger Raman shift in phosphosilicate glasses allows for amplification of signals at longer wavelengths in a single gain stage. This results in simplification in the amplifier design and increased efficiency as compared to those systems requiring multiple Raman shifts to achieve amplification in the same spectral bands. Further, while Raman gain can be increased by increasing the glass dopant concentration, it has been shown previously that the P_2O_5 concentration in useful P_2O_5-doped fibers is limited to approximately 14 mol% before attenuation exceeds the useful Raman gain [7].

To increase the threshold at which amplified Raman power is saturated due to SBS, the Brillouin gain bandwidth can be broadened, thereby reducing the gain available to any particular Brillouin frequency shift. One method for increasing the Brillouin gain bandwidth is to vary the core doping levels longitudinally along the fiber as the peak gain is proportional to material dependent parameters [5].

For the fiber presented in the *Experimental Results* section of this paper, the core concentration of P_2O_5 varied linearly from 9.6 mol% to 13.8 mol% over 660 m with a pure silica cladding. The dopant gradient was accomplished by adjusting the flow of reactants during the MCVD process used for preform manufacturing at the Institute of High Purity Substances, Russian Academy of Sciences. During fiber draw, the outer fiber diameter was varied from 100 µm (13.8 mol%) to 125 µm (9.6 mol%) so as to maintain single-mode operation as much as possible along the length of the fiber. The resulting fiber had a minimum attenuation of just over 2

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dB/km at 1550nm; refractive index and attenuation results are shown in Fig. 1.

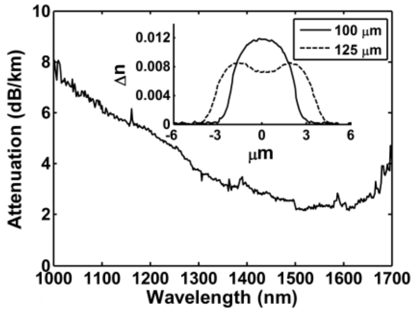

Fig. 1. Attenuation as a function of wavelength and refractive index profile (inset) for varying concentration phosphosilicate fiber.

III. Experimental Results

The Brillouin gain spectra for both a standard phosphosilicate Raman gain fiber (12.6 mol% doping – α = 0.9 dB/km at 1550 nm) and the varying concentration fiber (VCF) were measured at 1550 nm in a manner similar to [8], and are presented in Fig. 2. From the spectral plots we see that the gain bandwidth has been broadened from 46.3 MHz to 278.0 MHz, effectively reducing the peak gain by 6 dB in the VCF.

To assess the Raman amplification performance, both fibers were backward pumped by a 1.081 μm Yb^{3+} fiber laser (bandwidth ~1 nm) and seeded by 12 mW from a 1.262 μm narrow linewidth cw DFB (<6 MHz FWHM bandwidth). In order to avoid measurement variations along the length of the two fibers due to polarization effects, the seed laser polarization state was randomized prior to injecting it into the fibers. For the VCF, the lower concentration end was seeded as this configuration displayed the higher average Raman gain.

In the experiments, both peak cw Raman and SBS power were measured as a function of pump power. For 495 m of the standard fiber and 7.9 W of pump, the maximum Raman power measured was 580 mW before SBS limited any further increases in the output power. This resulted in an overall amplifier gain of 16.8 dB with 7.34% optical to optical conversion efficiency.

In contrast, for the 660 m VCF, we were able to increase pump power to 13.7 W resulting in 1.1 W of Raman amplified power and a 19.6 dB amplifier gain with 8.03% optical to optical efficiency. While this fiber is 165 m longer than the standard fiber tested, which should result in more significant SBS buildup, we were able to increase the Raman output power by nearly 90% or 2.8 dB, demonstrating the effectiveness of varying the core dopant concentration in suppressing SBS for increased Raman amplification. Additionally, it is expected that with further refinement in the preform manufacturing and consolidation process [9], the higher losses in the VCF can be reduced to levels experienced in standard phosphosilicate fibers, resulting in increased amplified power and optical conversion efficiency.

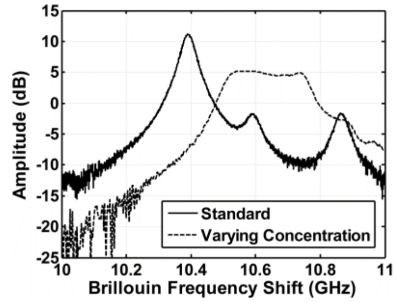

Fig. 2. Area normalized Brillouin gain spectra for standard and varying concentration phosphosilicate fibers.

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