AMPLIFIER DESIGN IMPLEMENTING HOLLOW-CORE PHOTONIC BANDGAP FIBER FOR FIBER-LASER BASED INFRARED FREQUENCY COMBS

JINGANG LIM, DANIEL V. NICKEL, BRIAN R. WASHBURN

Department of Physics, Kansas State University, 116 Cardwell Hall
Manhattan, KS 66503, USA

Infrared frequency combs based on mode-locked erbium-doped fiber lasers typically require an external amplifier since the pulses directly from the laser have insufficient peak power to generate an octave-spanning supercontinuum for self-referencing. Here we implement a unique, all-fiber erbium-doped fiber amplifier that uses hollow-core photonic bandgap fiber for pulse compression. Through a combination of experiment and numerical simulations we have demonstrated temporal compression in the hollow-core photonic bandgap fiber, thus increasing the pulse's peak power.

1 Introduction

Mode-locked erbium-doped fiber lasers produce the ideal frequency comb for infrared optical frequency metrology [1, 2]. By phase-locking the repetition rate, f_r, and the carrier-envelope offset frequency, f_{CEO} , to a stable RF or optical frequency, the resulting comb can be used as spectral ruler for measuring infrared optical frequencies [3].

One difficulty that fiber-laser based frequency combs have compared to their solid-state counterparts is that pulses directly from the laser do not have enough peak power to generate the octave bandwidth for f_{CEO} detection. External amplification is used to increase the pulse energy and decrease the pulse duration. This is accomplished using an erbium-doped fiber (EDF) amplifier [1] of three fiber sections (Fig. 1a). The first section contains a single-mode fiber (SMF) which has anomalous dispersion at 1550 nm. This section chirps the pulses before they are injected into the normal dispersion EDF section. Here the pulses experience gain but the normal dispersion prevents solitonic spectral broadening from occurring. In the post-chirp SMF section the dispersion is again anomalous and nonlinear solitonic effects are used to temporally compress the amplified pulses. Typically pulses can be temporally compressed by over 30% and experience larger than 10 dB gain.

Although this amplifier can produce short pulses, it does not efficiently use the bandwidth produced by nonlinear interactions in the EDF. The solitonic fiber nonlinearities in the post-chirp section cause pulse distortions and degrade the compression from the transform-limit. Instead of using nonlinear methods for pulse compression, we replace the nonlinear SMF with a hollow core photonic bandgap fiber (PBGF) in the post-chirp section. The effective nonlinearity of the PBGF is ~1000 times less than that of SMF since the pulse propagates in air in the PBGF, but it also exhibits anomalous dispersion (-11×10^{-5} fs^2/nm) for temporal compression. We have demonstrated pulse compression with an EDF amplifier implementing hollow-core PBGF for pulse compression. Furthermore, we have numerically modeled nonlinear pulse propagation by solving the nonlinear Schrödinger equation for propagation in the SMF, EDF, and PBGF sections.

2 Numerical and Experimental Results of Pulse Compression

The numerical and experimental results involve the amplification and temporal compression of 209 fs full-width at half-maximum (FWHM) pulses from an erbium-doped figure-eight laser. Numerical solutions to the nonlinear Schrödinger equation were performed to understand the pulse evolution though the amplifier. Care was taken to include the effects of dispersion, nonlinearity, gain, and gain dispersion. Figure 1b shows a numerical solution that illustrates pulse compression. The pulse propagates through 6 m of EDF and is compressed to 50 fs after 0.3 m of PBGF.

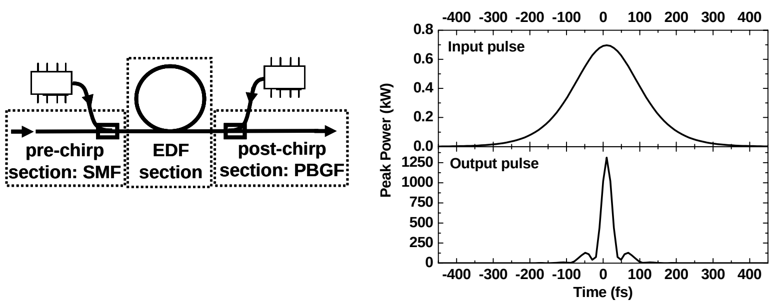

Figure 1. a) Schematic of the amplifier. b) Numerical simulation of pulse compression in the fiber amplifier. Top: the input, 210 fs transform-limited pulse from the figure-eight laser. Bottom: Output pulse from the amplifier showing temporal compression to 50 fs FWHM.

A series of experiments measured the pulse compression produced by an all-fiber amplifier design where the PBGF was directly spliced to the EDF [4]. The pulse duration was measured before the amplifier, after the EDF and after the PBGF. The duration increased from 210 fs to 800 fs in the EDF and the pulse was compressed to 110 fs in the PBGF. The difficulty in experimentally obtaining the 50 fs pulses arises due to a technical inability to cut off millimeter lengths of the PBGF.

References

1. B. R. Washburn, S. A. Diddams, N. R. Newbury, J. W. Nicholson, M. F. Yan, and C. G. Jørgensen, *Opt. Lett.* **29**, 250 (2004).
2. T. R. Schibili, K. Minoshima, F.-L. Hong, H. Inaba, A. Onae, H. Matsumoto, I. Hartl, and M. N. Fermann, *Opt. Lett.* **29**, 2467 (2004).
3. R. Fox, B. R. Washburn, N. R. Newbury, and L. Hollberg, *App. Opt.* **44**, 7793 (2005).
4. R. Thapa, K. Knabe, K. L. Corwin, and B. R. Washburn, *Opt. Express* **14**, 9576 (2006).