Mid-IR Supercontinuum Generation

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Abstract: Output pulses from an ultrafast holmium-praseodymium co-doped fiber ring laser are spectrally broadened in different highly nonlinear chalcogenide fibers. Moderate levels of broadening are achieved in step-index fibers and the effect is utilized for nonlinear pulse compression. Much larger broadening factors can be observed in suspended-core fibers and polymer-protected robust all-chalcogenide microwires. Under optimized conditions, an ultra-broadband supercontinuum spanning from 2 – 12 μm is generated.

OCIS codes: (320.6629) Supercontinuum generation; (140.3070) Infrared and far-infrared lasers; (060.3510) Lasers, fiber

1. Introduction

The availability of broadband radiation in the mid-infrared spectral region is of fundamental importance for application in spectroscopy, environmental monitoring and non-invasive breath analysis for early disease detection because virtually all molecules display fundamental vibrational absorptions in this region. For this reason, the mid-infrared (2 – 20 μm) is also referred to as the "molecular fingerprint" region [1-2]. Nonlinear spectral broadening is a powerful technique to transform relatively narrow-band laser light into broadband radiation which can reach extreme bandwidths spanning up to several octaves in the case of supercontinuum generation [3]. However, in order to drive nonlinear optical processes, high peak power seed sources are required. In the case of the mid-infrared, large and complex optical parametric amplifiers (OPAs) have therefore to be utilized for this task. In this paper, we discuss the spectral broadening that can be achieved by employing a non-amplified and relatively simple ultrafast fiber laser seed that consists of a holmium-praseodymium co-doped fluoride fiber as the gain material and which utilizes nonlinear polarization rotation (NPR) as mode-locking mechanism. The fiber laser emits at 2.9 μm, just beyond the atmospheric water vapor absorption which enables the generation of pulses with peak power levels as high as 37 kW directly from the oscillator [4].

2. Results and Discussion

A nonlinear fiber with large normal dispersion at the pump wavelength of 2.9 μm is required for nonlinear pulse compression as any self-phase modulation (SPM)-induced nonlinear chirp is then rapidly linearized due to the strong normal dispersion. Step-index As_2S_3 chalcogenide fiber is an excellent candidate for this task. We show that a very short length of this fiber is sufficient to broaden the laser spectrum to levels that support record-low pulse durations in the mid-infrared and that a simple grating pair compressor can be utilized to re-compress the pulses to durations approaching the single-cycle regime [5].

Larger levels of broadening can be achieved in AsSe suspended core optical fibers which can offer even smaller core diameters and thus higher nonlinearities. Moreover, the unique design of these fibers leads to a strong waveguide dispersion that can be used to shift the zero-dispersion wavelength (ZDW) to 3.5 μm, resulting in a shorter dispersion length compared to step-index fiber. We show that the generation of an octave-spanning supercontinuum becomes feasible with such fibers. In particular, due to the high refractive index contrast between the chalcogenide glass and the air cladding, a core diameter with sub-wavelength dimensions can be achieved in a suspended core fiber taper. This not only increases the nonlinear parameter, but the ZDW can also be shifted closer to the 2.9 μm pump wavelength.

Sub-wavelength diameter As_2Se_3 chalcogenide fiber tapers are known to feature extremely high nonlinearity parameters up to > 100 $W^{-1}m^{-1}$. However, such "microwires" are extremely fragile and can hardly be taken out of the fabrication rig without being damaged. We have therefore developed hybrid chalcogenide-polymer microtapers where a polymer coating provides superior mechanical robustness and flexibility [6]. For the generation of a broadband supercontinuum that extends across the entire mid-infrared fingerprint region, absorption of the evanescent field that propagates in the polymer coating becomes a problem. We have therefore developed a polymer-protected all-chalcogenide dispersion-engineered As_2Se_3/As_2S_3 microwire that avoids this issue. Using this

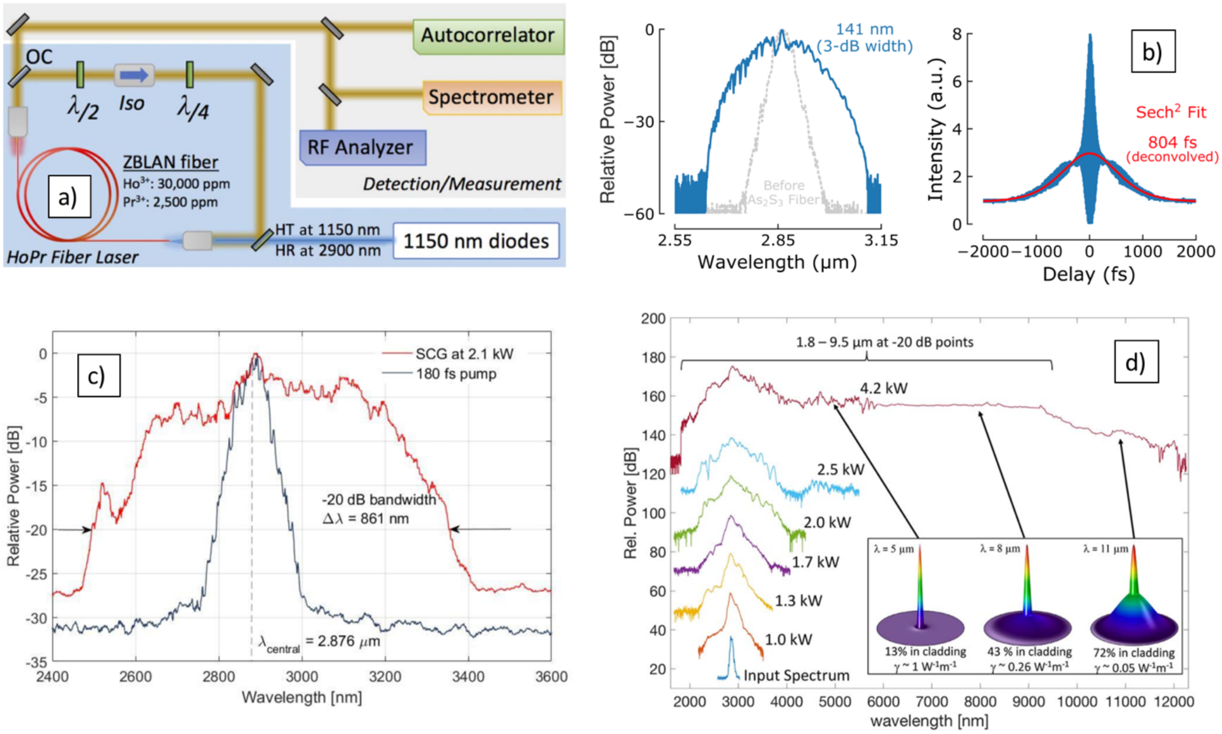

Fig.1. (a) Schematic of the ultrafast Ho-Pr co-doped fiber ring laser. (b) Spectrally (left) and temporally (right) broadened pulse after propagation through a 8 cm long As_2S_3 step-index fiber. (c) Spectral broadening after propagation through 39 cm of suspended core AsSe fiber. (d) Supercontinuum generated in a 5cm long As_2Se_3 microwire. The inset shows the mode profile at various wavelengths.

approach, an ultra-broadband supercontinuum spanning from 2 – 12 µm is generated [7]. We show that the long-wavelength edge of the supercontinuum is not limited by material absorption, but by the reduced nonlinearity due to the increased effective mode-field diameter of the long-wavelength spectral components that are generated in the microwire.

In summary, nonlinear spectral broadening of an ultrafast 3-micron class mid-infrared fiber laser oscillator in highly nonlinear chalcogenide fibers is reported. By employing advanced tapering techniques, a precise control of the dispersion profile of all-chalcogenide microwires can be achieved. This allows the generation of a broadband supercontinuum spanning the entire mid-infrared fingerprint region that is seeded by a compact and robust mid-infrared fiber laser oscillator, opening up the possibility to develop field-deployable mid-infrared spectroscopy systems for important application in environmental monitoring and healthcare.

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