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Invited Papers

# Modulation instability initiated high power all-fiber supercontinuum lasers and their applications

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ABSTRACT

High average power, all-fiber integrated, broadband supercontinuum (SC) sources are demonstrated. Architecture for SC generation using amplified picosecond/nanosecond laser diode (LD) pulses followed by modulation instability (MI) induced pulse breakup is presented and used to demonstrate SC sources from the mid-IR to the visible wavelengths. In addition to the simplicity in implementation, this architecture allows scaling up of the SC average power by increasing the pulse repetition rate and the corresponding pump power, while keeping the peak power, and, hence, the spectral extent approximately constant. Using this process, we demonstrate >10 W in a mid-IR SC extending from ~0.8 to 4 μm, >5 W in a near IR SC extending from ~0.8 to 2.8 μm, and >0.7 W in a visible SC extending from ~0.45 to 1.2 μm. SC modulation capability is also demonstrated in a mid-IR SC laser with ~3.9 W in an SC extending from ~0.8 to 4.3 μm. The entire system and SC output in this case is modulated by a 500 Hz square wave at 50% duty cycle without any external chopping or modulation. We also explore the use of thulium doped fiber amplifier (TDFA) stages for mid-IR SC generation. In addition to the higher pump to signal conversion efficiency demonstrated in TDFAs compared to erbium/ytterbium doped fiber amplifier (EYFA), the shifting of the SC pump from ~1.5 to ~2 μm is pursued with an attempt to generate a longer extending SC into the mid-IR. We demonstrate ~2.5 times higher optical conversion efficiency from pump to SC generation in wavelengths beyond 3.8 μm in the TDFA versus the EYFA based SC systems. The TDFA SC spectrum extends from ~1.9 to 4.5 μm with ~2.6 W at 50% modulation with a 250 Hz square wave. A variety of applications in defense, health care and metrology are also demonstrated using the SC laser systems presented in this paper.



## 1. Introduction

We demonstrate high power, all-fiber integrated, SC laser sources from the visible to the mid-IR (~0.45–4.5 μm) wavelengths following a common framework for the SC generation process. Our approach utilizes amplified picosecond/nanosecond laser diode pulses, which are broken down into shorter, higher peak power pulses through MI and then coupled into an SC generation fiber to achieve further spectral broadening. We show that the SC generation approach outlined in this paper allows for each stage to be customized for the required wavelength output, and enables the scalability of average power in the SC by increasing the repetition rate and the corresponding pump power in the amplifier stages. Using this process, we demonstrate >10 W in a mid-IR SC extending from ~0.8 to 4 μm, >5 W in a near IR SC extending from ~0.8 to 2.8 μm, and >0.7 W in a visible SC extending from ~0.45 to 1.2 μm. Modulation capability is also demonstrated in our mid-IR SC system, where the entire system and the SC output are modulated with a 500 Hz square wave at 50% duty cycle without any external signal modulation or chopping equipments. Also presented in this paper, is a high efficiency mid-IR SC system using a TDFA based power-amplifier stage. The TDFA based system generates a mid-IR SC extending out to ~4.5 μm, up to ~270 nm further in wavelength than the longest spectrum from EYFA based systems presented here. In addition, the TDFA system is seen to be ~2.5 times more efficient in generating mid-IR SC beyond

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3.8 μm with respect to the amplifier pump powers, than the corresponding EYFA based systems. Finally, we demonstrate applications in spectroscopy, health care and metrology enabled by the broad bandwidth and the high power of the SC systems presented in this paper.

Supercontinuum generation describes the process by which narrow band optical pulses undergo substantial spectral broadening through the interplay of a number of nonlinear optical interactions in the medium, to yield a broadband spectrally continuous output. Since its first observation in bulk media by Alfano [1], SC generation has been studied extensively and numerous applications using SC have been proposed and demonstrated. Broadband SC generation in optical fibers have been of particular interest due to the unique advantages offered by their long optical interaction lengths, high nonlinearity, and potential applications in optical telecommunications. In addition fiber based SC lasers are potentially compact, reliable and robust, which make them attractive candidates over conventional bulk lasers sources for practical applications. With the development of mature gain fibers, high power pump diodes, optical fibers of various materials, geometries and dispersion profiles; it is now possible to construct a broadband SC fiber laser platform for almost any wavelength of interest from the UV to the mid-IR.

The use of picosecond and nanosecond pump pulse regimes with MI initiated SC generation has enabled the development of high average power, broad band SC sources. In addition, this pump regime provides easier access to a range of attractive SC properties such as a high degree of spectral flatness and relative simplicity in implementation compared to many SC systems that use mode-locked lasers. Fig. 1 illustrates our architecture for MI initiated SC generation and provides a platform for generating SC in multiple wavelength regions. We utilize this framework to demonstrate SC systems in the mid-IR, near-IR and the visible wavelengths by selecting the appropriate gain fiber and SC generation fiber. In addition to the simplicity of implementation, we demonstrate that this architecture for SC generation also allows for the scalability of the SC time averaged power by simply increasing the repetition rates and the pump power in the amplifier stages.

In each system, we begin with ~1.5 μm picosecond/nanosecond laser diode pulses that are amplified through a series of cascaded fiber amplifier stages. These amplified pulses are then launched into a length of SMF fiber, where interaction between the nonlinearity and anomalous dispersion breaks up the quasi-CW input pulses into a train of solitons through MI and significantly increases the peak power. Thus, while many SC lasers use mode-locked femtosecond lasers to achieve high peak powers, MI enables the use of long pulses from compact laser diode sources. The generated solitons will undergo further spectral broadening in the SC fiber, due to a variety of nonlinear effects such as self phase modulation, soliton self frequency shift, Raman scattering and parametric four wave mixing. The SC fiber chosen depends on the SC wavelength requirements: photonic crystal fiber (PCF) following a frequency doubler for visible wavelengths, fused silica for near-IR wavelengths and ZBLAN for mid-IR wavelengths.

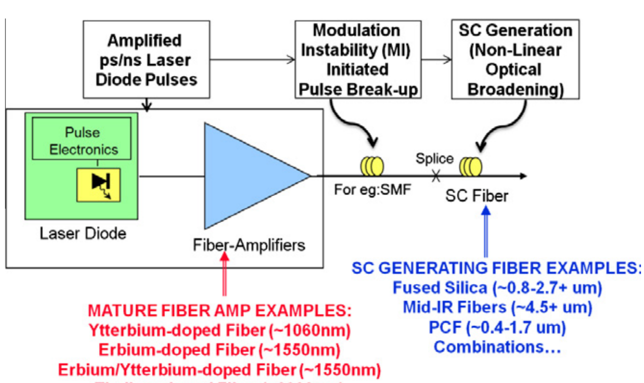


**Fig. 1.** Architecture for MI initiated SC generation process: amplified pump pulses followed by pulse breakup in single-mode fiber followed by spectral broadening in SC fiber.

In this paper, we focus specifically on high power, all-fiber integrated mid-IR SC laser systems. A high power mid-IR SC source has a wide variety of applications, such as spectroscopy [2], IR countermeasures [3], free space communications [3], optical tissue ablation [4] to name a few. Conventional mid-IR laser sources including optical parametric amplifiers [5], quantum cascaded lasers [3], synchrotron lasers [6] and free electron lasers [7] have been used to demonstrate some of these applications. In comparison, an all-fiber, mid-IR SC laser has no moving parts, output in a single spatial mode and operate at room temperature. SC lasers also generate a broad spectrum covering the entire near IR and the mid-IR simultaneously, which can improve the selectivity of remote chemical sensing [8] and real time optical metrology [9]. In addition, direct signal modulation functionality is also desirable for SC laser sources to eliminate the need for external signal modulation or chopping equipments, which is difficult to implement in the mode-locked laser based systems. By initiating the SC generation through MI, we eliminate the need for a mode-locked laser in our SC systems and are able to use commercial off-the-shelf parts from the mature telecommunications and fiber optics industry.

The recent interest to incorporate a TDFA stage in a mid-IR SC laser is driven by the higher pump-to-signal conversion efficiency demonstrated in Tm-doped gain fibers compared to EYFAs. For example, slope efficiency as high as ~56% is demonstrated in Tm-doped gain fibers [10] compared to EYFAs, which have demonstrated slope efficiencies of ~38% in comparable fiber geometries [11]. Since the TDFA gain band is in the 1.9–2.1 μm region, a signal input at ~2 μm is required. Various techniques have been reported in the literature to generate ~2 μm pulses as input to the TDFA. For example, by using a mode-locked Er fiber laser with polarization maintaining components operating at 1557 nm followed by an EYFA, a Raman shifting soliton pulse to ~2 μm in a 12 m length of high NA fiber has been demonstrated by Imeshev and Fermann [12]. A subsequent dispersion-managed large mode area TDFA stage generates pulses with up to 230 kW peak power at ~2 μm. Another approach generates ~750 fs long ~1.95 μm pulses using a saturable absorber based carbon nanotubes in a Tm-doped fiber laser cavity [13]. Other approaches using 1.55 μm laser diode pulses, instead of mode-locked lasers have also been demonstrated. For instance, one approach involves three successive orders of cascaded Raman wavelength shifting from 1.53 μm to 1.94 μm in germanium-doped fused silica fibers with an NA of ~0.41 [14]. Another approach involves gain switching a Tm-doped fiber cavity with a modulated 1.55 μm pump to generate 10 ns long, 2 μm pulses [15]. In our approach, we first generate an SC extending across the thulium amplifier gain band, which is then further amplified in the TDFA power amp stage to act as a pump for further spectral broadening in the mid-IR. This is discussed in detail in Section 3.1.3.

This article is organized as follows. We begin with a brief literature review of recently reported SC sources. Then, in Section 3, we describe the SC experimental setups following the framework set in Fig. 1 and present the SC generation results for each of the wavelength regions. We first describe the high power mid-IR SC laser with ~10.5 W in an SC extending from ~0.8 to 4 μm. Then, we demonstrate a system where the power amp output peak power is scaled up to ~20 kW, to push the ZBLAN spectrum out further in wavelength to ~4.3 μm. Modulation capability is also demonstrated in this section. We then present the TDFA based high