Power scalable mid-infrared supercontinuum generation in ZBLAN fluoride fibers with up to 1.3 watts time-averaged power

Chenan Xia, Malay Kumar, Ming-Yuan Cheng, Ravi S. Hegde, Mohammed N. Islam*, Almantas Galvanauskas, Herbert G. Winful, and Fred L. Terry, Jr.

Department of Electrical Engineering and Computer Science, University of Michigan,
1301 Beal Avenue, Ann Arbor, Michigan 48109
caxia@umich.edu

Mike J. Freeman

**Omni Sciences Inc., 647 Spring Valley Drive, Ann Arbor, Michigan 48105*

Marcel Poulain and Gwenael Mazé

Le Verre Fluoré, Campus KerLann, F-35170 Bruz, Brittany, France

Abstract: Mid-infrared supercontinuum (SC) extending to ~4.0 µm is generated with 1.3 W time-averaged power, the highest power to our knowledge, in ZBLAN (ZrF_4-BaF_2-LaF_3-AlF_3-NaF...) fluoride fiber by using cladding-pumped fiber amplifiers and modulated laser diode pulses. We demonstrate the scalability of the SC average power by varying the pump pulse repetition rate while maintaining the similar peak power. Simulation results obtained by solving the generalized nonlinear Schrödinger equation show that the long wavelength edge of the SC is primarily determined by the peak pump power in the ZBLAN fiber.

OCIS codes: (060.2290) Fiber materials; (060.2390) Fiber optics, infrared.

References and links

1. G. P. Agrawal, *Nonlinear Fiber Optics*, 3rd edition, (Academic, San Diego, 2001).
2. I. T. Sorokina and K. L. Vodopyanov, eds., *Solid-State Mid-Infrared Laser Sources*, (Springer-Verlag, Berlin Heidelberg, 2003).
3. S. Moon and D. Y. Kim, "Generation of octave-spanning supercontinuum with 1550-nm amplified diode-laser pulses and a dispersion-shifted fiber," Opt. Express **14**, 270-278 (2006).
4. A. K. Abeeluck, C. Headley, and C. G. Jørgensen, "High-power supercontinuum generation in highly nonlinear, dispersion-shifted fibers by use of a continuous-wave Raman fiber laser," Opt. Lett. **29**, 2163-2165 (2004).
5. C. L. Hagen, J. W. Walewski, and S. T. Sanders, "Generation of a continuum extending to the midinfrared by pumping ZBLAN fiber with an ultrafast 1550-nm source," IEEE Photon. Technol. Lett. **18**, 91-93 (2006).
6. C. Xia, M. Kumar, O. P. Kulkarni, M. N. Islam, F. L. Terry, Jr., M. J. Freeman, M. Poulain, and G. Mazé, "Mid-infrared supercontinuum generation to 4.5 µm in ZBLAN fluoride fibers by nanosecond diode pumping," Opt. Lett. **31**, 2553-2555 (2006).
7. C. Xia, M. Kumar, M.-Y. Cheng, O. P. Kulkarni, V. V. Alexander, M. N. Islam, A. Galvanauskas, F. L. Terry, Jr., M. J. Freeman, M. Poulain, and G. Mazé, "0.8-4.5 microns supercontinuum generation in ZBLAN fluoride fibers scaled up to 1.25 W power," presented at Conference on Lasers and Electro-Optics CLEO 2006, Long Beach, Calif., May 21–26, 2006, postdeadline paper, CPDA10.
8. T. Hohage and F. Schmidt, "On the numerical solution of nonlinear Schrödinger equations in fiber optics," ZIB-report 02-04, (2002), ftp://ftp.zib.de/pub/zib-publications/reports/ZR-02-04.pdf.
9. A. Saissy, J. Botineau, L. Macon, and G. Maze, "Raman scattering in a fluorozirconate glass optical fiber," J. De Physique Lettres **46**, 289–294 (1985).
10. J. M. Parker, "Fluoride glasses," Annu. Rev. Mater. Sci. **19**, 21-41 (1989).
11. Y. Dureste, "Raman amplification in fluoride glass fibres," Electron. Lett. **21**, 723-724 (1985).

#77831 - $15.00 USD Received 7 December 2006; revised 22 January 2007; accepted 28 January 2007

1. Introduction

We demonstrate mid-infrared (mid-IR) supercontinuum (SC) generation in ZBLAN (ZrF_4-BaF_2-LaF_3-AlF_3-NaF...) fluoride fibers with the highest time-averaged power reported to date, for the first time to our knowledge. Using an erbium/ytterbium co-doped cladding-pumped fiber amplifier (EYFA) to amplify a modulated laser diode, SC ranging from 0.8 µm to ~4.0 µm with 1.3 W average power is generated in 13 m ZBLAN fibers following 3 m length of standard single mode fiber (SMF). The time-averaged power of the SC can be scaled by varying the pulse repetition rate, i.e. pulse duty cycle, while maintaining the similar peak power. The SC generation process is also simulated by solving the generalized nonlinear Schrödinger equation (NLSE) numerically [1]. By taking parameters of the different pump systems into consideration, simulations show that the spectral width of the SC is mainly determined by the pump peak power and matches with the experimental results. The average power of the SC is limited by the pump power coupled into the ZBLAN fiber.

The all-fiber SC light source provides a new platform in the mid-IR wavelength regime. Compared to the conventional mid-IR light source, such as optical parametric oscillators and quantum cascaded lasers [2], the ZBLAN SC produces the entire spectrum in the single spatial mode and operates at room temperate. Therefore, the mid-IR light source could be a key-enabling technology for various applications such as spectral fingerprinting, semiconductor process control and combustion monitoring. For example, multiple absorption lines and spectral patterns of chemical samples under test may be simultaneously monitored to achieve higher sensitivity and selectivity. Moreover, the average power of the SC can be scaled up by increasing the pump pulse repetition rate and using higher power pump lasers.

SC generation in various optical fibers has been widely studied under different pumping sources. For example, SC ranging from 0.9 µm to 1.7 µm with 12 mW average power was generated in fused silica fibers by amplified nanosecond laser diode pulses [3]. Abeeluck et al also reported SC generation with ~550 nm bandwidth and 3.2 W average output power in highly nonlinear fibers pumped by continuous Raman fiber laser [4]. In ZBLAN fluoride fibers, SC extending out to 3.4 µm with 5 mW average power was generated by using femtosecond mode-locked laser [5]. We also generated SC to ~4.5 µm with ~23 mW average power by using amplified nanosecond laser diode pulses [6]. By using laser diode pulses and varying the pulse duty cycle, we demonstrate a mid-IR SC source of more than 3000 nm bandwidth with the average power scaled up to 1.3 W power in ZBLAN fibers.

For our experiments, the SC is generated in a two-stage process [6,7]. In the first stage SMF fiber, the nanosecond pulses are broken up into femtosecond pulses by modulation instability. The spectrum is then broadened through the interplay of self-phase modulation, parametric four-wave mixing and stimulated Raman scattering in the second stage ZBLAN fiber. Because the SC spectrum is broadened in the fiber through nonlinear phenomena, the generation process is related to the peak power of the pump pulses instead of the average power. Therefore, by changing the repetition rate of the pump pulses while maintaining a similar pulse peak power, the average power of the SC can be scaled up or down with nearly identical spectrum.

2. Experimental setup and results

The pump laser is a fiber amplifier system, seeded with an electric-pulse-driven distributed Bragg reflector diode laser at 1548 nm (Fig. 1). To suppress the stimulated Brillouin scattering, the signal spectrum of the laser is broadened to ~1 nm bandwidth by chirping the phase segment of the diode. The system consists of three main amplification stages: a standard single mode core pre-amplifier, a 7 μm core double-clad fiber amplifier, and a 25 μm core double-clad fiber amplifier. The pre-amplifier stage is a 5.5 m long erbium-doped fiber amplifier (EDFA) pumped by a 320 mW 1480 nm pump diode. The second stage is an 8 m long single mode EYFA, which has a 7 μm NA=0.17 core, and a 130 μm NA=0.46 inner pump cladding. Up to 4 W pump power at 980 nm is coupled into the gain fiber. The amplified spontaneous emission of the first and second stage fiber amplifiers is suppressed by

#77831 - $15.00 USD Received 7 December 2006; revised 22 January 2007; accepted 28 January 2007

using an acousto-optic modulator and a band-pass filter. The last stage is a 5 m long large-mode-area EYFA, which has a 25 μm NA=0.1 core and a 300 μm NA=0.46 cladding. Large-mode-area fiber is used to avoid nonlinear effects in the fiber core and single mode output can be achieved by properly selecting coupling lens to match the mode of the input beam with the fundamental mode of the gain fiber. With ~30 W coupled pump power, the system outputs ~7 W amplified signal power, corresponding to pulse energy of ~23.3 μJ and pulse peak power of ~11.7 kW for 2 ns pulses at 300 kHz repetition rate.

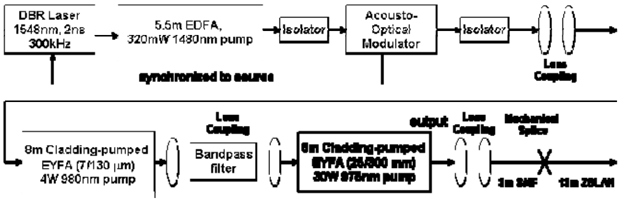

Fig. 1. Experimental setup comprising three-stage fiber amplifier followed by laser diode

SC is generated in the SMF fiber followed by ZBLAN fiber. SMF fiber is used to breakup the nanosecond laser pulses, and the spectrum is then broadened in the ZBLAN fiber. The free space output light is first lens coupled into the SMF fiber with ~60% coupling efficiency. The output of the SMF fiber is then mechanically spliced to the ZBLAN fibers with ~3 dB coupling loss. Both ends of the SMF fiber and ZBLAN fiber are angle cleaved to minimize the feedback in the system. To avoid the thermal damage of the fiber under high power, the coating of the ZBLAN fiber input end is removed and the bare fiber is contacted with an air-cooled heat sink. We observe some optical damage spots in the ZBLAN fiber with coupled average power >2 W, which we believe is due to the contaminants in the fiber. Two ZBLAN fibers are used in the experiment, a) FL#1 has a core diameter of 7 μm, cladding diameter of 125 μm and cut-off wavelength of 2.75 μm, and b) FL#2 has a core diameter of 8.5 μm, cladding diameter of 125 μm and cut-off wavelength of 1.75 μm [6]. By using long-cut-off-wavelength fiber, the loss of the fiber on the long wavelength side can be reduced due to lower bend-induced loss. SC spectrum from 700 nm to 1750 nm is measured by using an optical spectrum analyzer, while the longer wavelength components are obtained by using a grating-based spectrometer with a liquid-nitrogen cooled InSb detector at 100 nm intervals.

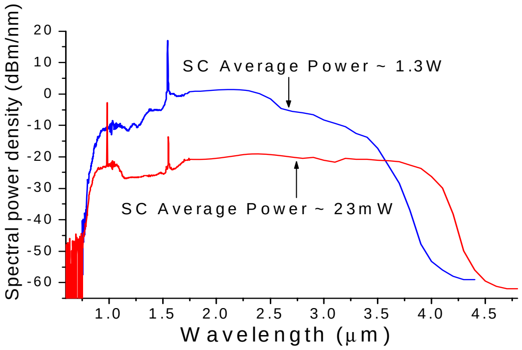

Fig. 2. SC spectrum from a) 3m SMF fiber followed by 13m FL#1 in high power setup, and b) 1m SMF fiber followed by 8m FL#1 in low power setup

SC with 1.3 W time-averaged power is generated from 3 m SMF fiber followed by 13 m FL#1 (Fig. 2). The SC spectrum extends from ~0.8 μm to beyond 4.0 μm by coupling ~3 kW (~1.9 W) peak (average) pump power into the ZBLAN fiber, which implies a SC power conversion efficiency from the pump of >60%, i.e. 1.3 W SC power divided by 1.9 W coupled pump power. The SC has a bandwidth of >1000 nm as the 3 dB drop and of >2700 nm as the

Received 7 December 2006; revised 22 January 2007; accepted 28 January 2007

20 dB drop from the highest spectral power density of ~1.5 dBm/nm (1.4 mW/nm). The low power result, which is obtained in a multi-stage single-mode EDFA system [6], is also illustrated in Fig. 2. By pumping 1 m SMF fiber plus 7 m ZBLAN fiber at 4 kW peak power, SC with an average power of ~23 mW is generated from ~0.8 µm to more than 4.5 µm. Compared to the low power results, the SC average power is scaled up by ~65x times to ~1.3 W for the high power results. Also, we observe that the SC long wavelength edge of the high power results does not extend as far as that of the low power results. We attribute the difference to the different pump system setup, as explained below.

By replacing the second stage FL#1 with 10 m FL#2, SC extending from ~0.8 to 3.6 µm is generated with 1.2 W average power with ~3.5 kW coupled peak pump power [Fig. 3(a)]. The SC spectrum has a bandwidth of ~2000 nm with only ~5 dB drop from the peak spectral power density and the SC conversion efficiency from the pump is >50%. Moreover, the long wavelength edge of the SC is similar to the low power results with the 3.6 µm edge, which is limited by the short cut-off wavelength and high bend-induced loss of the fiber [6]. Therefore, the SC generation is independent of the pump laser sources and amplifiers. By optimizing the length of the fiber in each stage, SC with comparable spectrum can be generated in different pump systems.

To compare the spectral shape of the SC pumped by similar pump power, similar lengths of FL#2 are tested in both low power and high power systems. By directly coupling ~1.5-2 kW peak pulse power into 60-80 m length of ZBLAN fibers, SC ranging from 0.8 µm to ~3.4 µm has been generated [Fig. 4(b)]. For the 5 kHz repetition rate, SC has an average power of ~13 mW and spectral power density of ~-20 dBm/nm over the 2-3 µm wavelength range. By increasing the repetition rate to 500 kHz in the high power system, the average power of the SC is increased to 1.25 W with the spectral power density increased to ~0 dBm/nm in the same wavelength range. We observe that SCs with similar spectral shape are generated with the SC average power scaled up by a factor of 100, which is consistent with the 100x increase of the pulse repetition rate. As described above, the long wavelength edge is limited by the bend-induced loss of the ZBLAN fiber and low pump peak power [6, 7]. Therefore, the SC system can scale the time-average power by varying the pulse repetition rate while maintaining the same spectral shape by keeping the similar peak pump power.

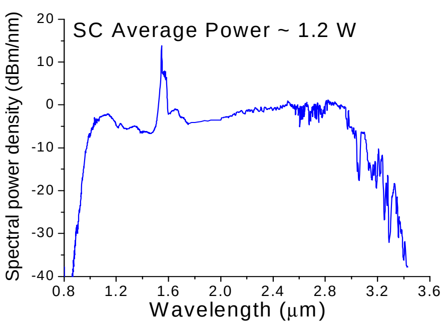

Fig. 3. SC spectrum from 3m SMF fiber followed by 10m FL#2

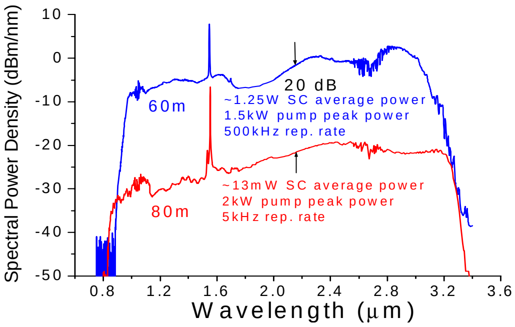

Fig. 4. SC spectrum from a) 80 m FL#2 pumped by 2 kW peak power at 5 kHz rep. rate, b) 60 m FL#2 pumped by 1.5 kW peak power at 500 kHz rep. rate

3. Computer simulation and comparison of experiments

To study the difference of the SC spectra generated from the low and high power pump systems, the generalized NLSE has been adopted and solved numerically. The complex envelope $A(z,\tau)$ of a pulse, under the slowly varying approximation satisfies the generalized NLSE given by [1],

$$\frac{\partial A}{\partial z} = (\hat{D} + \hat{N})A$$
$$\hat{D} = -\frac{i}{2}\beta_2 \frac{\partial^2 A}{\partial \tau^2} + \frac{1}{6}\beta_3 \frac{\partial^3 A}{\partial \tau^3} + \frac{i}{24}\beta_4 \frac{\partial^4 A}{\partial \tau^4} - \frac{\alpha}{2}$$
$$\hat{N} = i\gamma(1 + \frac{i}{\omega_0}\frac{\partial}{\partial t})\int_{-\infty}^{+\infty}[(1 - f_R)\delta(t) + f_R h_R(t)] \mid A(z, t - t') \mid^2 dt'$$

where the pulse moves along z in the retarded time frame $\tau = t - z/v_g$ with the center angular frequency of ω_0. The linear terms in the differential operator $\hat{D}$ account for the second (β_2), third (β_3) and the fourth order (β_4) dispersion as well as the loss (α) of the fiber. The terms in the operator $\hat{N}$ result from nonlinear interactions, which describe self-phase modulation, self-steepening and stimulated Raman scattering effects. In particular, the effective nonlinearity is defined as $\gamma = n_2\omega_0 / cA_{eff}$, where n_2 and A_{eff} are the nonlinear refractive index and effective mode area of the fiber respectively. In addition, $h_R(t)$ represents the Raman response function, and f_R is the fractional contribution of the Raman response to the nonlinear polarization.

The NLSE described above has been solved by adaptive split-step Fourier method with the initial pulse shape as the known boundary value [1, 8]. The step size is determined and dynamically adjusted by the nonlinear gain in each section. Because of the large bandwidth of the SC compared to the Raman gain spectrum of the silica and ZBLAN glasses, approximation of the Raman gain as a linear function of frequency is not valid any more. Therefore, we take into account the actual Raman gain spectrum of the specific fiber in the simulator [1, 9]. Also, material dispersion of the fiber glass is used for both SMF and ZBLAN fiber. For the SMF fiber, the effective nonlinearity γ is 1.6 $W^{-1}km^{-1}$ and Raman gain peak g_R equals to 6.4×10^{-14} m/W [1]. For the ZBLAN fiber, the effective nonlinearity γ and the Raman gain peak g_R are assumed to be same as that of silica glass [10, 11]. The simulated spectrum is averaged by every 100 nm to match the data acquisition interval of the experiment.

Figure 5(a) illustrates the simulation results compared with the experimental data in the low average power setup. In both the experiment and simulation, the generated SC has a spectrum ranging from ~0.8 µm to ~4.5 µm. The peak and features around 980 nm in the experiments are due to the undepleted pump from the amplifier, which is not included in the simulation. Also, the long wavelength side of the SC spectrum is higher and has distinct peak features in the simulation compared to the experimental results. Because the long wavelength side of the SC is mainly generated through stimulated Raman scattering, we believe that the differences between the simulation and experiment come from the approximation of the Raman gain spectrum in the simulation. Super-Gaussian pulses of 100 ps pulse width are used in the simulation to emulate the 2 ns pulses in the experiment. We observe that the soliton collision process stops for the pulses walking off from the main 100 ps pulse, which is due to the delayed response of the Raman scattering in the time domain and the anomalous dispersion of the ZBLAN fibers in the mid-infrared wavelength regime. Therefore, intra-pulse cascaded Raman wavelength shifting will be the dominant nonlinear process in these pulses, which could give rise to the peaks in the long wavelength side. The long wavelength edge of the spectrum around 4.5 µm is loss limited by the glass absorption of the ZBLAN materials [6].

For the high average power case [Fig. 5(b)], we observe that the SC long wavelength edge is limited to ~4 µm in both the experiments and simulations. The SC spectrum does not extend as far as that of low average power results. Because the peak power in the high average power case is only ~3 kW, which is lower than the 4 kW peak power in the low average power result, the nonlinear spectrum broadening effect is less and the long wavelength edge is limited.

Figure 5(c) illustrates the long wavelength edge of the simulated SC, which is measured as 40 dB drop from the continuum level, under different pump powers. We can observe that the long wavelength edge extends further to beyond 4 µm when the peak pump power is larger than 3~4 kW. Therefore, SC extending to ~4.5 µm can be generated by increasing the peak power in the ZBLAN fiber. In addition, there are not any sharp features around 1 µm in the SC compared to the low power results since the pump system is backward pumped and the light from the pump is lens-coupled into the SMF fiber. On the other hand, the disagreement between the experiment and simulation in the long wavelength edge is because of the approximation of the Raman effects and pulse width in the simulation as described above, as well as the diminished wave-guiding capability of the fiber in the long wavelength side. For the ZBLAN glass fiber, the refractive index change of the core and cladding is inversely proportional to the temperature [10]. One possible reason is that the loss of the fiber in the long wavelength side increases with the rising temperature difference between the core and cladding under high average power condition.

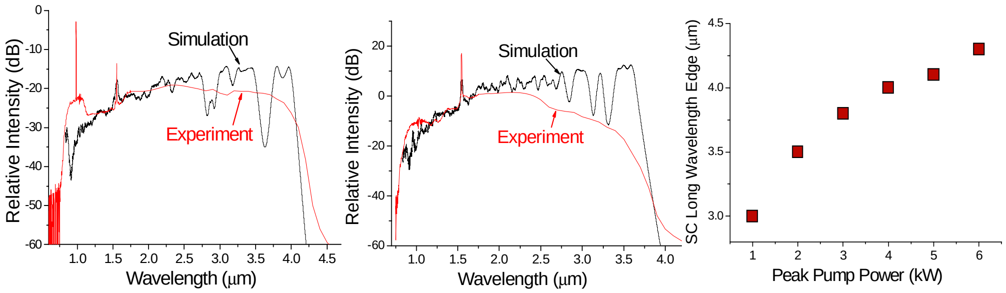

Fig. 5. (a). SC spectrum after 1.25m SMF followed by 8m FL#1 at 4kW peak power in the low average power setup, (b). SC spectrum after 3m SMF followed by 11m FL#2 at 3kW peak power in the high average power setup, (c). SC spectrum after 3m SMF followed by 11m FL#2 as a function of peak pump power in the high average power setup

4. Discussion

We scale up the SC average power by increasing the pulse repetition rate of the pump system and using EYFAs. The time-averaged power of the SC is increased by a factor of 60, i.e. from ~23 mW at 5 kHz repetition rate to 1.3 W at 300 kHz repetition rate, which is consistent with the change of the pulse repetition rate. EYFAs are used to replace the EDFAs in the low power case to provide higher average power while keeping the similar pulse peak power, which ensures the same nonlinear process.

The average power and the spectral width of the SC in the high power setup are limited by the average and peak power coupled into the ZBLAN fiber from the pump system. The spectral width is limited to ~4 µm because of the relatively low peak power (3 kW). Simulation shows the spectral width of the SC can be further extended to ~4.5 µm by increasing the pump peak power to more than 4 kW. Therefore, by substituting the current pump system with higher power system, both the average power and the spectral width of the SC can be further scaled up. It should be noted that as the average power is increased, better thermal management of the fiber is required. The air-cooled heat sink needs to be replaced by the water cooled heat sink and the ZBLAN fiber can be coated with metal-based coating to facilitate the thermal conduction.

In conclusion, we generated SC in ZBLAN fluoride fibers of 1.3 W average power with more than 3000 nm bandwidth. The SC average power is scaled by changing the pulse repetition rate of the pump system and using EYFAs, while maintaining the same peak power and pulse width. Simulation results are obtained by solving the generalized NLSE numerically and agree with the experiments. The average power of the SC can be further scaled up by using higher power pump systems and implementing better purification process during the fabrication of the ZBLAN fibers.

Acknowledgments

This work was supported by ARO W911NF-04-C-0078 and DARPA W31P4Q-05-C-0159. The University of Michigan is partially funded through sub-contracts from Omni Sciences, Inc.

Received 7 December 2006; revised 22 January 2007; accepted 28 January 2007